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Temporal and spatial variations in salt pond environments and implications for fish and invertebrates

Lonzarich, David George, M.A.

San Jose State University, 1989

TEMPORAL AND SPATIAL VARIATIONS IN

SALT POND ENVIRONMENTS AND

IMPLICATIONS FOR FISH AND INVERTEBRATES

A Thesis

Presented to

The Faculty of the Department of Biological Sciences
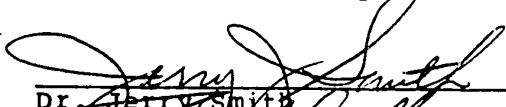
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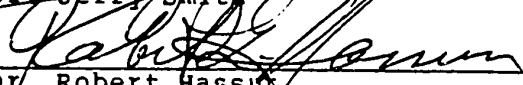of the Requirements for the Degree
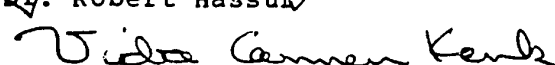
Master of Arts

By

David George Lonzarich

May, 1989

Approved for the Department of Biological Sciences
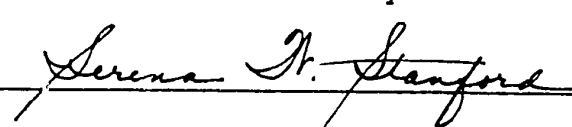
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Dr. Jerry Smith

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Dr. Robert Hassur

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Dr. Vida Kenk

Approved for the University

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ABSTRACT

I studied water quality and the distribution of aquatic species in a series of brackish and hypersaline (20-85 ppt) salt evaporation ponds in south San Francisco Bay between May 1985 and November 1986. Physical and chemical characteristics in the ponds were distinct from, and often more stressful than, the surrounding Bay. Invertebrate abundance varied substantially among ponds and seasons. Brine shrimp (Artemia salina) and copepods were the dominant invertebrates in high salinity ponds, whereas benthic and epibenthic invertebrates were most abundant in low salinity ponds. Slight changes in salinity in the range of 30-40 ppt produced large changes in community composition.

Fifteen fish species were collected in the ponds. Six species were able to reproduce in some ponds, and topsmelt (Atherinops affinis) and longjawed mudsucker (Gillichthys mirabilis) were able to reproduce to 75 ppt salinity. The remaining nine species occurred as transients from the Bay.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Over one century ago the south San Francisco Bay shoreline was bordered by many kilometers of salt marshes and mudflats that supported a diverse and productive flora and fauna. Since that time, however, the area of these wetlands has been steadily diminishing, and today less than 15 percent of the wetlands in south San Francisco Bay remain undeveloped (Nichols et al., 1986). Some of these marshes have been converted for agricultural, commercial, or residential purposes, but most have been diked for solar salt production. Presently, the Leslie Salt Company harvests Bay salt from over 18,000 hectares (44,000 acres) of solar salt evaporation ponds in San Francisco Bay, including over 13,600 hectares in south San Francisco Bay.

The loss of south San Francisco Bay wetland habitats has had immeasurable effects on many marsh dependent species, such as waterfowl, shorebirds, and the endangered California clapper rail (Rallus longirostris obsoletus) and salt marsh harvest mouse (Reithrodontomys raviventris raviventris). Although wetlands converted for agricultural use retained limited wildlife value (Josselyn, 1983), the value to wildlife of those wetlands converted for commercial or residential use is negligible. Salt ponds form a series

1

of habitats, defined primarily by their salinity, which can range from brackish to highly concentrated brine. Bay water is diverted into intake ponds and circulates through a series of ponds, where salinity progressively increases by the process of solar evaporation. This process continues until the saturation point of sodium chloride is reached, at approximately ten times the concentration of sea water. The pond habitats created by these conditions are diverse and have been exploited to varying degrees by many wetland species. The hypersaline salt ponds, in particular, provide a unique habitat type in San Francisco Bay that has permitted some species of birds not historically common in the Bay, or more typically associated with hypersaline lakes, to flourish (i.e., eared grebe (Podiceps nigricollis), black-necked stilt (Himantopus mexicanus), white pelican (Pelecanus spp.), California gull (Larus californicus), and caspian tern (Sterna caspia)) (Anderson, 1970; T. Harvey, USFWS, pers. comm.)

South San Francisco Bay salt ponds and their levees provide roosting, feeding, and nesting habitats for many species of waterbirds. Some of these species rely on the ponds only for specific uses (e.g., roosting), whereas others use the ponds almost exclusively (i.e., phalaropes (Phalaropus spp.), bonaparte gull (Larus philadelphia) and

2

eared grebe). The great majority of the dabbling ducks (i.e., northern shoveler (Anas clypeata), northern pintail (Anas acuta), and American wigeon (Anas americana)) in south San Francisco Bay roost or feed in the salt ponds, as do many diving ducks (i.e., ruddy duck (Oxyura jamaicensis) (Takekawa et al., 1988). The ponds are also integral to the ecology of shorebirds in south San Francisco Bay. Of the several hundred thousand shorebirds that migrate through San Francisco Bay each winter, most feed in the tidal mudflats at low tides and roost or feed in the shallow water ponds during high tides (Stenzel and Page, 1988).

Most biological studies conducted on San Francisco Bay salt ponds have had a very narrow focus, with the greatest emphasis placed on the biology of waterbirds (Gill, 1977; Anderson, 1970; Swarth et al., 1982; Howard, 1983) and brine shrimp (Artemia salina) (Berthelemy-Okazaki, 1986; Baker, 1966; Swarth et al., 1982). The vast majority of the waterbird studies have been surveys which have focused on the distribution of wintering and breeding populations, but others, such as that conducted by Swarth et al. (1982), attempted to explain the distribution of waterbirds with respect to salinity, prey availability, pond depth, and other environmental factors. In general, these studies demonstrated that pond salinity and depth greatly affect

3

bird distribution patterns. Brine shrimp are the main component in the food chain of the hypersaline ponds (where salinities exceed 70 ppt). Despite a paucity of quantitative studies on bird feeding behavior (Howard, 1983), brine shrimp are undoubtedly a critical food source for waterbirds that feed in the ponds.

Fish and invertebrates found in the ponds have seldom been studied, although it is apparent that salt pond fish provide a very important prey resource for many species of birds, including the endangered least tern (Feeney, pers. comm.). Carpelan (1957) conducted the only comprehensive study of the fish communities and physio-chemistry of south San Francisco Bay ponds. He found that topsmelt (Atherinops affinis) and long-jawed mudsucker (Gillichthys mirabilis) were widespread in the ponds below 70 ppt, but he found few other species even at lower salinities.

The primary purpose of this one and one-half year study (April 1985 - November 1986) was to describe the structure and dynamics of the fish communities of a series of six low to moderate salinity (20-85 ppt) salt evaporation ponds in south San Francisco Bay near Alviso. Distribution patterns were compared to spatial and temporal variations in pond hydrology, invertebrate prey composition, and prey abundance. Age structure, breeding status, and feeding

4

behavior of the most common fish species were also
investigated. The study is intended to provide a general
understanding of the ecology of the ponds under present
solar evaporation operations and also to provide a basis for
their potential management within the San Francisco Bay
National Wildlife Refuge should commercial solar evaporation
be abandoned.

STUDY AREA

The study area is located immediately north of Alviso
in south San Francisco Bay (hereafter referred to as South
Bay), and encompasses six salt ponds bounded to the north by
Coyote Creek, to the southwest by Alviso Slough, and to the
east by Southern Pacific railroad tracks (Fig. 1). Like
other South Bay salt ponds, the Alviso ponds are large
(ranging in size from 100 to 150 hectares) and shallow (mean
depth less than 1 meter). The ponds in this unit are linked
with the South Bay and the mouth of Alviso Slough at Pond A9
through two, 1.2 meter diameter culverts located in the
western levee adjacent to Alviso Slough. When the culverts
are open from late spring through late fall, brackish water
from Alviso Slough enters Pond A9 at high tide and flows by
gravity through a 1.2 meter diameter culvert into Pond A10.
From Pond A10, the water circulates through regulated
culverts into Ponds A11, A12, and A13. The water in Pond
A13 is typically pumped into Pond A15, however, it may also
be pumped into Pond A14, where it is stored until needed in
Pond A15. An additional intermittent source of water is
Pond A8, a high salinity pond located directly across from
Pond A11 on the west edge of Alviso Slough. A pipe under
Alviso Slough diverts water from Pond A8 into Pond A11.

6
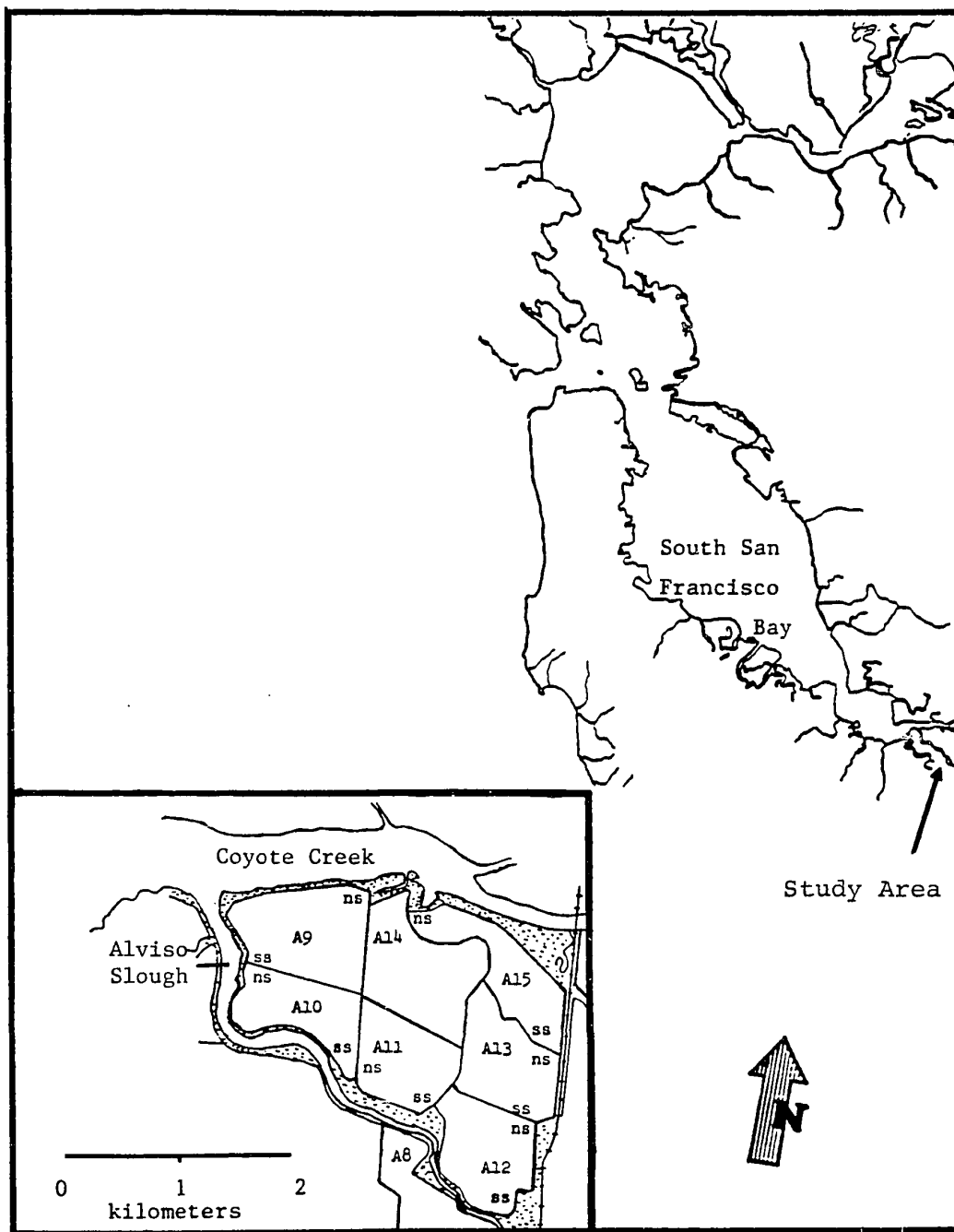
Figure 1: Location of study area in south San Francisco Bay and northshore (ns) and southshore (ss) stations for study ponds A9 – A13 and A15.

7

MATERIALS AND METHODS

Water Chemistry

Water quality characteristics in the six ponds were measured at northshore (NS) and southshore (SS) monitoring sites between April 1985 and October 1986. Changes in water level were determined weekly from staff gauges in each pond. Measurements of surface salinity (American Optics Refractometer), dissolved oxygen (YSI model 54 DO meter), pH (Cole Parmer pH meter), and water temperature were made on site biweekly (weather permitting) through April 1986, then monthly through October 1986. Diurnal fluctuations in surface water temperature, dissolved oxygen, and pH were determined on one typical day every three months in Ponds A9 and A12. Monthly pond surface temperatures ranges were also determined from permanently stationed maximum and minimum thermometers. Secchi depths were determined in the afternoon once a month from March 1986 through October 1986.

Afternoon (1300-1600) water column profiles for dissolved oxygen, temperature, pH, and salinity were examined in the six ponds seasonally from the fall of 1985 to the fall of 1986. Morning measurements (0800-1000) were made during the summer and fall of 1986.

Invertebrates

Benthic and epibenthic invertebrates were examined seasonally from the six ponds from the fall of 1985 to the fall of 1986 to determine general abundance of potential prey for fish. In Ponds A9 and A10, epibenthic invertebrates were removed from algal samples, which were collected by hand or dip net from the benthos, and stored in 4 percent formaldehyde. During each sampling period, two to three epibenthic and infauna samples were collected from Ponds A9 and A10, and one sample was collected from each of Ponds A11-A15 using an Eckman dredge (21.2 cm x 21.2 cm). Sediment samples were stored on ice in the field and returned to the laboratory where they were sieved using a 0.5 mm sieve and stored in 4 percent formaldehyde. Specimens were later identified to order (Actiniaria, Copepoda and Ostracoda), genus, or species (all other taxa). For Ponds A9 and A10, and for Ponds A11-A15 collectively, the taxa were ranked for general abundance as either abundant (numerous and collected at every site); common (moderately abundant, collected at every site); uncommon (moderately abundant not collected at every site) or rare (low numbers, not collected at every site).

Seasonal zooplankton surveys were conducted in each pond from December 1985 through November 1986. Two replicate

9

surface plankton tows with an 0.30 m diameter net and 10 um mesh were made along 50 m transects in the borrow pits along the south shore margin of each pond. Plankton collected in the net were washed into specimen vials and fixed in 4 percent formaldehyde. In the laboratory, samples were washed with tap water to remove salt water, and oven dried at 50-60 C degrees for 24-48 hours. Total dry weight, species composition, and relative densities were then determined for each sample.

Fish

Fish were collected from the six ponds between the months of August 1985 and September 1986 by beach seine, minnow trap, and variable mesh gill net. Two beach seines were used. One measured 15.2 m x 1.8 m with 0.95 cm square mesh and the second was a 30.5 m x 1.8 m net with 0.5 cm square mesh. Although seining was generally effective, it was not suitable for every pond. In Ponds A9 and A10, for example, dense bottom vegetation and steep shorelines made seining difficult. By the spring of 1986, when macroalgal growth was highest, efforts to seine these two ponds were discontinued. The timing of seine surveys in Ponds A11 through A15 was irregular, although sampling was generally seasonal. Two to three samples were taken from each pond on

each date.

Beginning in January 1986, minnow traps were added to improve collections of small pelagic and benthic species. Typically, two unbaited minnow traps were set for 24-48 hours in each pond. Sampling was conducted monthly in Ponds A9 and A10, bimonthly in Pond A11 and seasonally in Ponds A12 through A15.

Large fish not collected by minnow trap and seines were collected with gill nets. Two net types were used in this study. One net measured 36.6 m x 1.8 m with 2 panels of 1.2 cm and 1.9 cm square mesh, and the second was 38 m x 1.8 m with 5 panels ranging from 1.2 to 5 cm square mesh. One or two nets were generally set in each pond for approximately 24 hours. Surveys were conducted monthly in Ponds A9 and A10, bimonthly in Pond A11, and seasonally in Ponds A12 through A15. All individuals collected were measured to the nearest mm standard length (SL). Most of the fish collected were immediately released, but several individuals from each catch were preserved for subsequent determinations of feeding habits, age structure, and reproductive condition.

Food habits were determined for the most abundant fish collected in the ponds. Samples were categorized by season and pond type, and 5-10 individuals were examined from each sample. Prey percent numbers, percent volume, and frequency

11

of occurrence were recorded for the contents of the stomach and upper one-third of the intestine in each fish.

Age structure and growth rates of the most common fish species were determined by length frequency distributions and by aging and back calculations from scale annuli. Length frequency distributions were also used to document the spawning seasons. For topsmelt, two additional methods were used to evaluate reproductive maturity and spawning season. Gonad volume and total fish volume were measured and the percent of the total volume accounted for by the gonads in individual fish was calculated. The diameter of individual eggs was also determined and qualitatively ranked into three categories of development. Eggs were either immature/spent (range 0.0-0.4 mm), maturing (0.4-1.0 mm), or ripe (>1.0 mm) (as described by Schultz 1933).

Biological results, including productivity and individual species abundances, were compared to environmental variables by correlation and multiple regression.

RESULTS

Salinity

Figures 2a-b show the mean monthly salinities measured at northshore sites in the six Alviso ponds. Salinities ranged from 20 ppt to more than 80 ppt. There was some overlap among ponds, but mean salinities in Ponds A9 and A10 were much lower and more stable than in Ponds A11 to A15. Salinities in Pond A9 and A10 averaged 30 ppt, and ranged from brackish to slightly hypersaline (20-40 ppt). In Ponds A11 through A15, salinities were typically greater than 35 ppt and variable. Mean salinities in these ponds were from 50 to 68 ppt during the study and ranged from 23 ppt to 84 ppt. Seasonal changes in salinity were greatest in Pond A11, which received low salinity water from Pond A10 and high salinity water from Pond A8. Salinities in Pond A11 were 50 ppt higher than those in adjacent Pond A10 in January 1986 (84 vs 33 ppt), and well below sea water concentrations in September 1986 (23 ppt). Fluctuations in salinity within Ponds A12, A13, and A15 were less extreme than those measured in Pond A11, but still varied by over 35 ppt over the course of the study.

Within each pond there were slight, but detectable, gradients in salinity across ponds and with depth. Mean

13
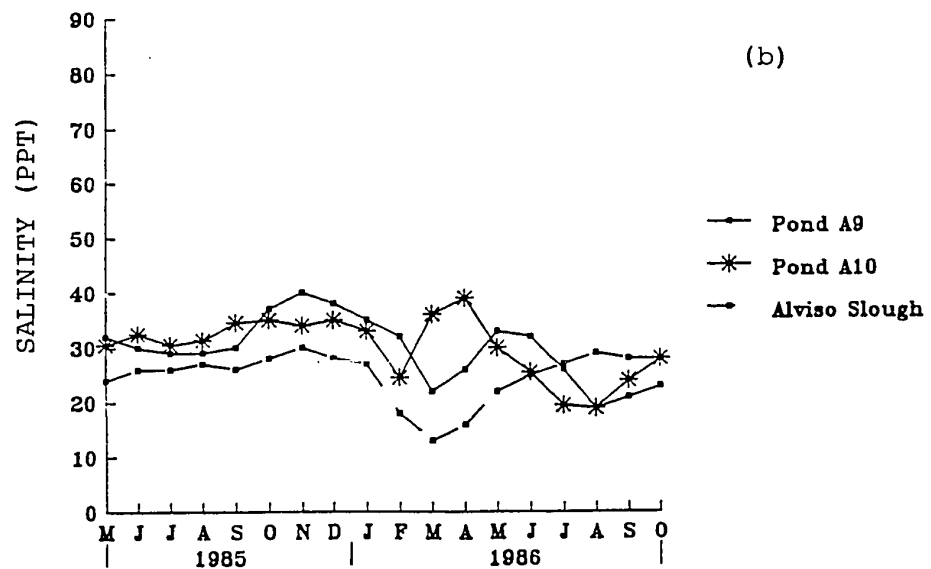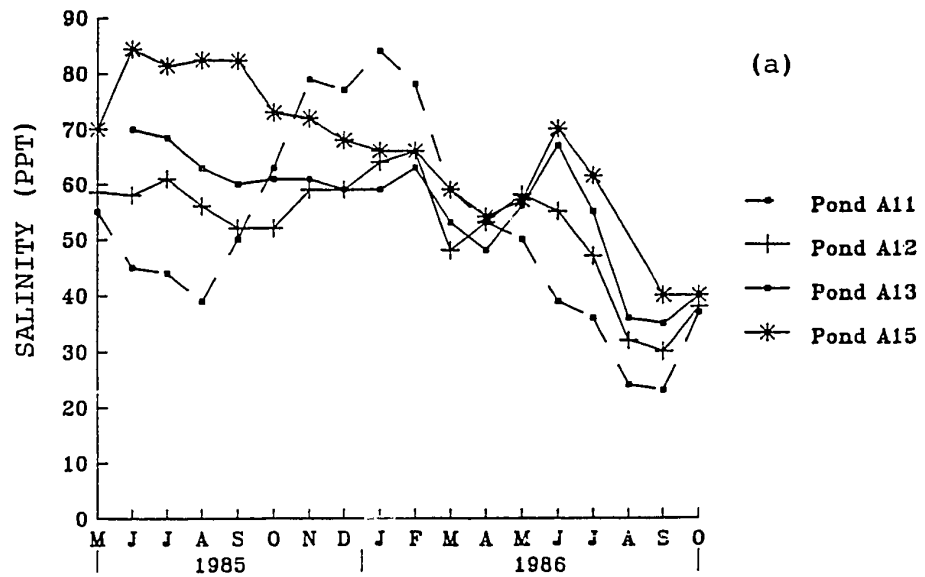
Figure 2a-b: Mean monthly surface salinities measured at NS stations in Alviso salt ponds from May 1985 to October 1986.

14

salinities at southshore sites were 2 ppt greater than means at northshore sites. The greatest salinity gradient with depth was found in Pond A9 during June of 1986, following the introduction of water from Alviso Slough; surface salinity at that time was 25 ppt, while bottom salinity, at 1.5 meters, was 31 ppt. Greater salinity gradients may develop briefly following rainstorms; however, measurements could not be made during these times because wet levee roads were impassable.

Seasonal and spatial variations in pond salinities were affected by the salinity and duration of surface water inputs (i.e., from Alviso Slough or preceding ponds), and temporal differences in rates of evaporation and precipitation. Surface water inputs into the ponds (i.e. from Alviso Slough and Pond A8) were seasonal and regulated by the Leslie Salt Company. The diversion of water from Alviso Slough into the ponds depended on pond water levels, and both pond and Slough salinities. Generally, water from Alviso Slough was diverted into Pond A9 in the months of highest Slough salinities, between June and November. The timing of water diversions from Pond A8 into Pond All varied annually; diversions in 1985 were more frequent than in 1986.

Temporal change in salinity within the two low salinity ponds is probably constant from year to year, but the range of salinities and mean concentrations may vary annually depending on rates of evaporation and precipitation. In 1986 the highest salinities in Pond A9 and A10 were recorded in the spring, just prior to the introduction of brackish Alviso Slough water. Salinities dropped in the summer despite increased rates of evaporation, because the salinity of the in-flowing Slough water (range 20-25 ppt) during these months was lower than that of the ponds (30-35 ppt). By early fall, however, both evaporation and high Alviso Slough salinities forced pond salinities upward once more. The two ponds differed in salinity trends in the late winter 1986. At that time salinities in Pond A9 declined, while salinities in A10 increased. The decline in Pond A9 paralleled that found in the four high salinity ponds (Ponds A11 to A15) and was due to a heavy rainstorm in February. Salinity increased in Pond A10 when high salinity water was diverted into this pond from Pond A11 following the storm. In winter, salinities varied with the amount and timing of precipitation. Heavy winter storms, such as during February of 1986, directly reduced salinities in Ponds A9 and A10, and also indirectly altered pond salinities by reducing the Slough salinities in the subsequent months.

16

Seasonal and annual variations in source water inputs to Pond A11 and from Pond A14 into A13 and A15 had a profound effect on annual salinity trends in the high salinity ponds. In the summer and fall of 1985, the surface water inputs into Pond A11 came from both Pond A10 and Pond A8, whereas over the same period in 1986 only water from Pond A10 was moved into Pond A11. As a result of these input differences, salinities in Ponds A11 through A15 were high (40-85 ppt) and relatively stable in the summer and fall of 1985, but fell sharply (25-40 ppt) during the same period in 1986. The highest salinities in Pond A11 were recorded in the late winter and spring of 1986 when high salinity water from Pond A8 was pumped through Pond A11. Salinities peaked in the other three ponds later that spring when high salinity water from Ponds A11 and A14 began to circulate through the system. Heavy rains of February 1986 reduced salinities in the ponds by as much as 20 ppt, but evaporation increased salinities by as much as 20 ppt over the following two months.

Depth

With the exception of Ponds A9 and A15, the ponds were subject to large seasonal fluctuations in water depth (Fig. 3a-b). In Ponds A10 through A13, where maximum relative

17
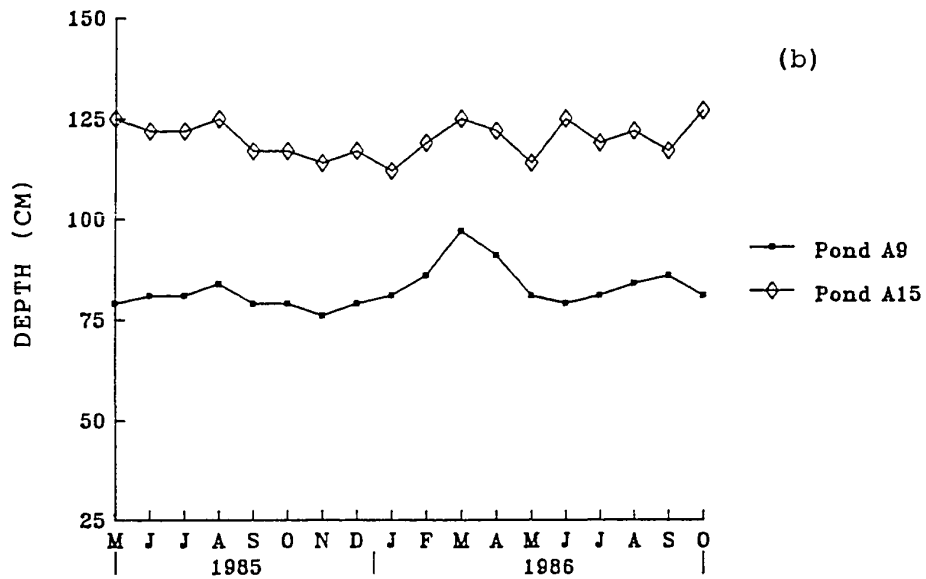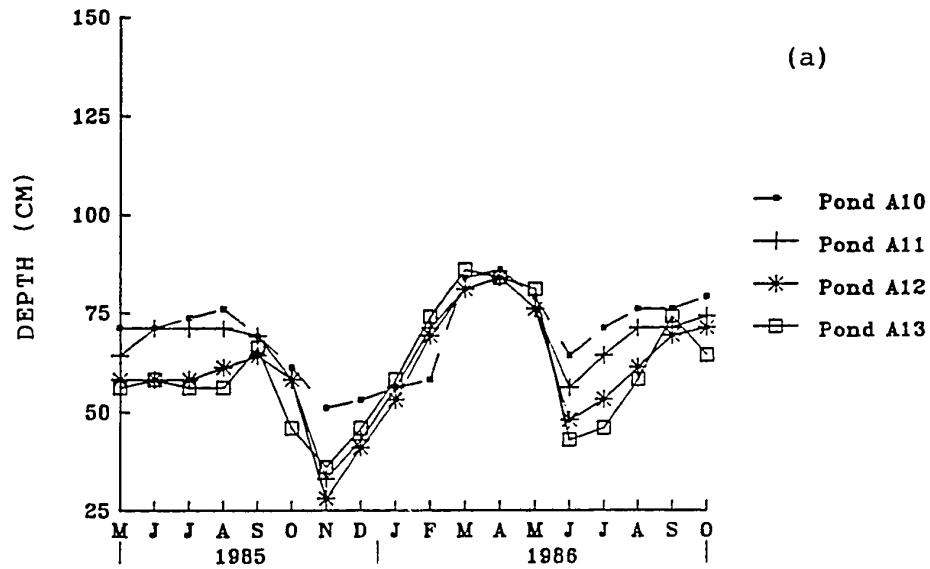
Figure 3a-b: Mean monthly depth measurements (cm) recorded at shoreline stations in Alviso salt ponds from May 1985 to November 1986.

18

depths at shoreline sites measured less than 0.9 meters,
depths varied by as much as 0.6 meters or 67 percent. These
fluctuations in pond depth occurred biannually, and often
took place rapidly. For example, in the fall of 1985 water
depths in Ponds A11-A13 fell by as much as 40 cm in less
than one month. Depth at shoreline sites was typical of
most of the pond, with the exception of the remnant tidal
slough channels and dredged (borrow) pits bordering the pond
perimeter. During periods when water levels were lowest,
the only areas deeper than 0.6 meters were the borrow pits
and slough channels.

Seasonal fluctuations in pond depth were affected by
rates of evaporation and precipitation, and the timing and
magnitude of regulated water diversions. In Ponds A10-A13,
water diversions at Pond A13 were the major cause of
seasonal change. As water was diverted from this pond, the
lowered water level of A13 resulted in gravity flow from
pond A9 through A12 to refill A13. When this water was
pumped in the late fall or late spring, there was no
incoming flow from Alviso Slough to compensate for these
diversions, and consequently water levels in Ponds A10-A13
dropped dramatically (i.e. fall of 1985 and spring of 1986).
Water depths in Ponds A9-A13 increased during the summer and
fall, when inflows from Ponds A10 and A8 were greater than

19

outflows. Seasonal changes in rates of precipitation and
evaporation played an unpredictable, but important role in
regulating pond depths. A heavy storm in February 1986
increased pond depths by 10 cm in a single week.
Evaporation reduced depths by as much as 8 cm per month.

Water temperature

Mean monthly morning northshore surface water
temperatures ranged from 6 to 25 degrees C over the one and
one-half year study, and were very similar among all six
salt ponds (Fig. 4). Mean monthly water temperature at
northshore sites ranged 6-10 degrees C (Fig. 5). The
highest temperature recorded in the ponds was 28 degrees C
in July 1986, and the lowest was 5 degrees C in December
1985 (Fig. 5).

Surface water temperatures measured in the morning at
northshore sites closely paralleled air temperatures during
most months of the study (Fig. 6). Diurnal patterns of air
and water temperature variation were also similar. Diurnal
fluctuations in pond temperatures were most extreme in the
spring of 1986 (Table 1), when pond A9 temperatures varied
by 6 C over 18 hours on 16 May 1986. Diurnal temperature
changes were 4 degrees C or less in November 1985, July
1985, and February 1986. Thermal stratification was
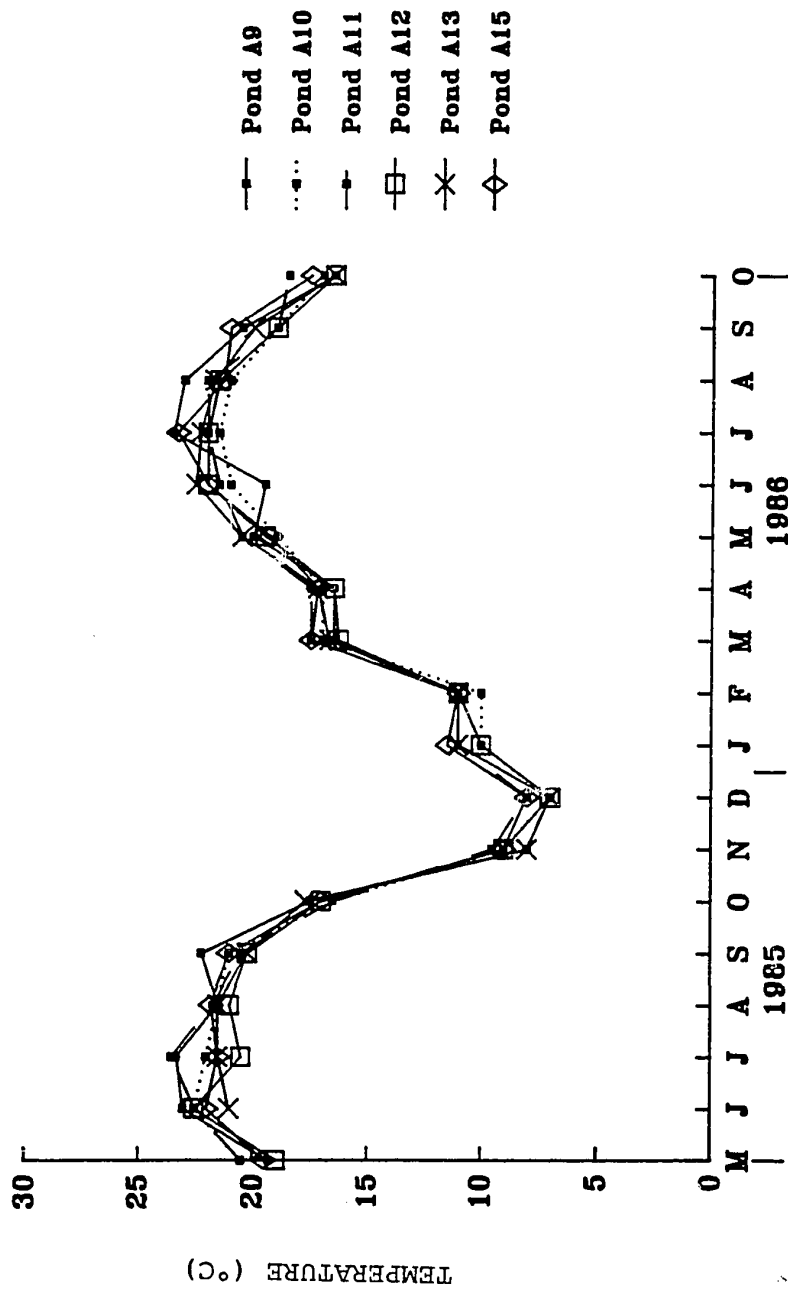
Figure 4: Mean monthly surface water temperatures measured at NS stations during morning in Alviso salt ponds from May 1985 to October 1986.

21
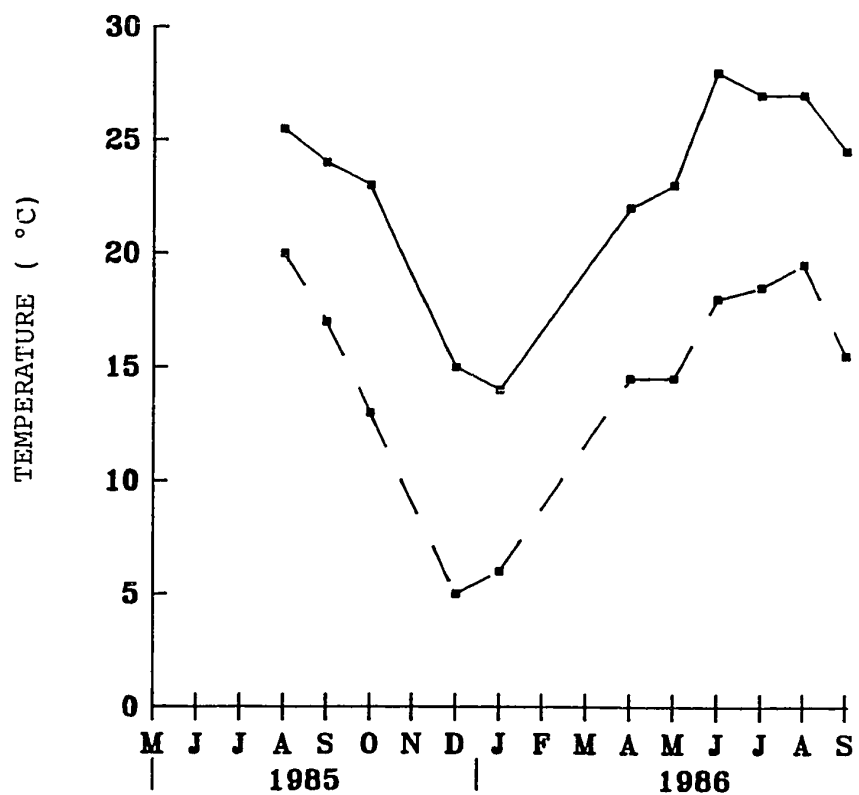
Figure 5: Mean monthly maximum (solid line) and minimum (dashed line) surface water temperatures measured in Alviso salt ponds from August 1985 to September 1986.

22
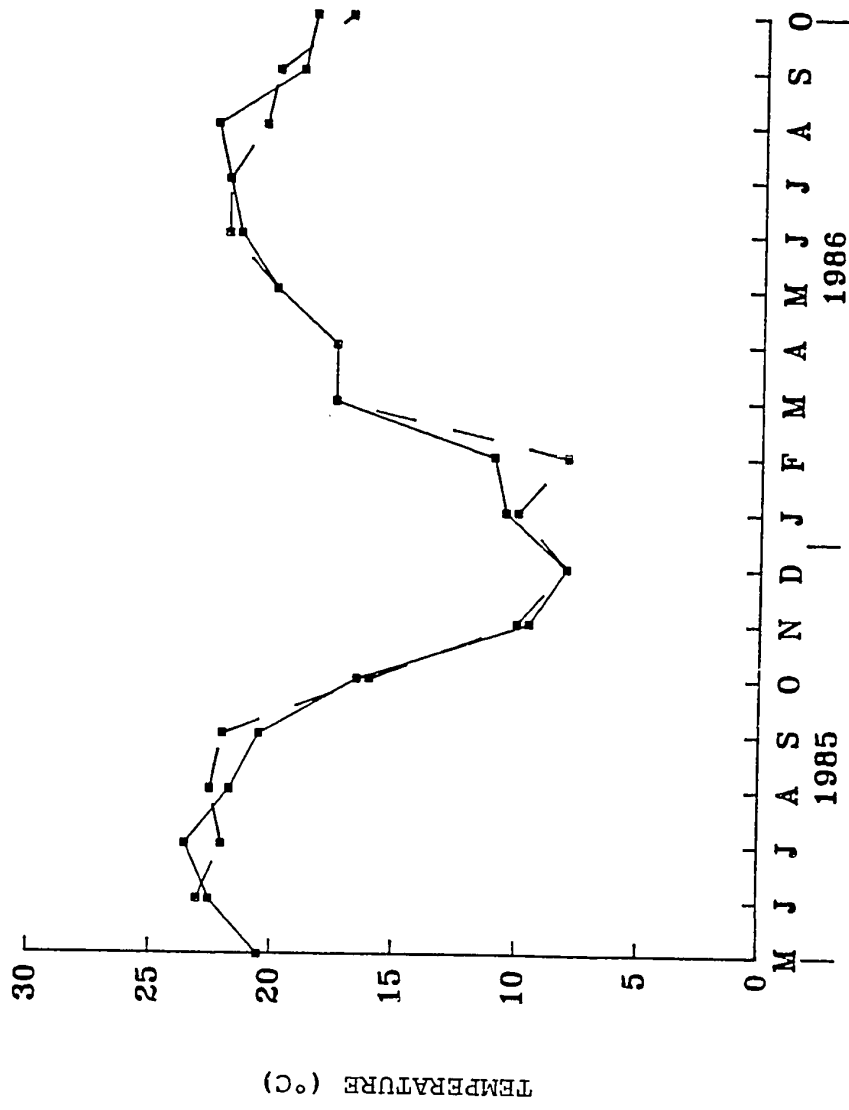
Figure 6: Mean monthly morning air (dashed line) and surface water (solid line) temperatures measured at NS station in pond A12 from May 1985 to October 1986.

23
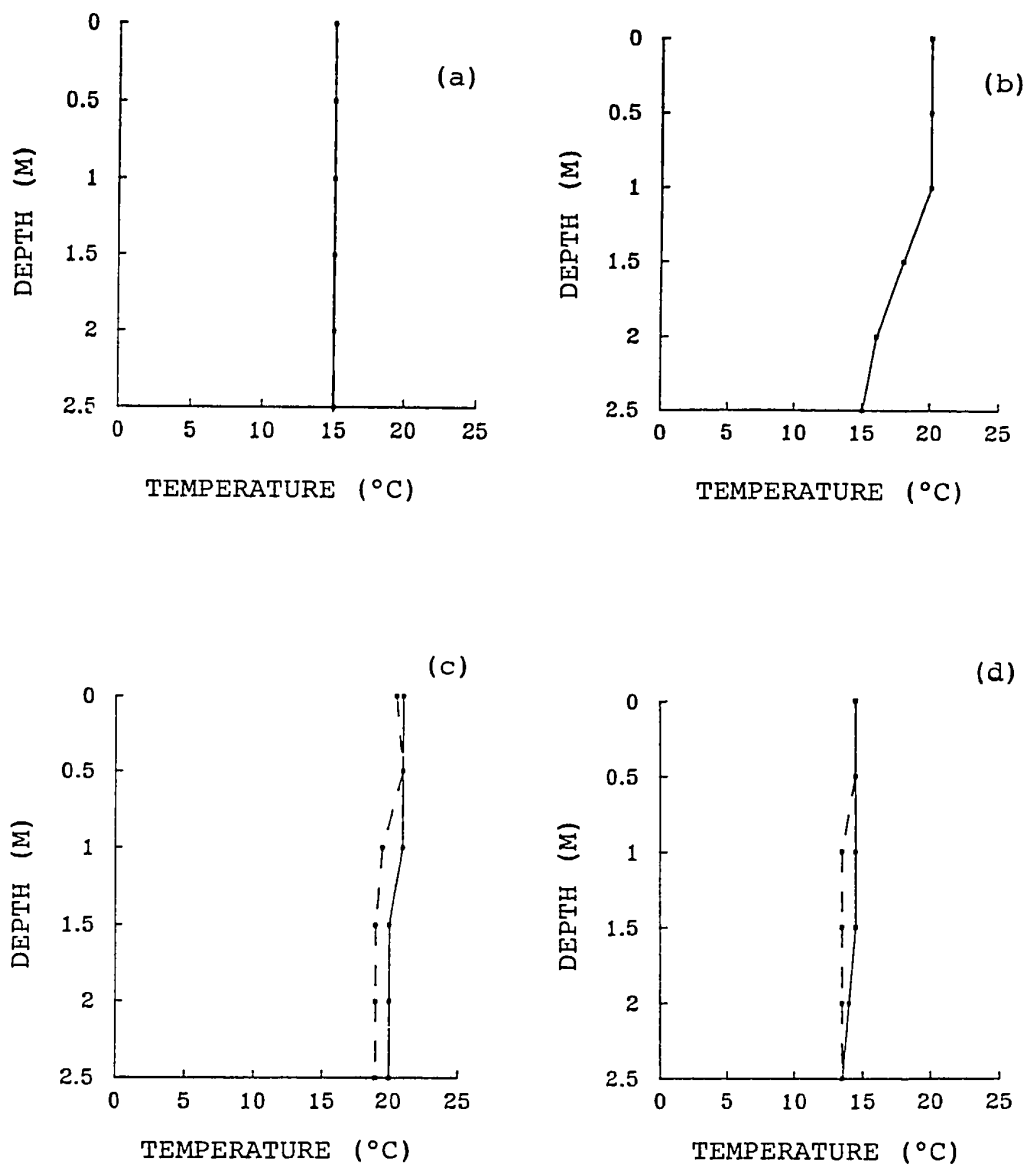
Figure 7a-d: Morning (dashed line) and afternoon (solid line) temperature profiles from Pond A13 for seasonal sampling dates (a) 22 Jan 1986; (b) 22 Mar 1986; (c) 28 Jun 1986; (d) 22 Nov 1986.
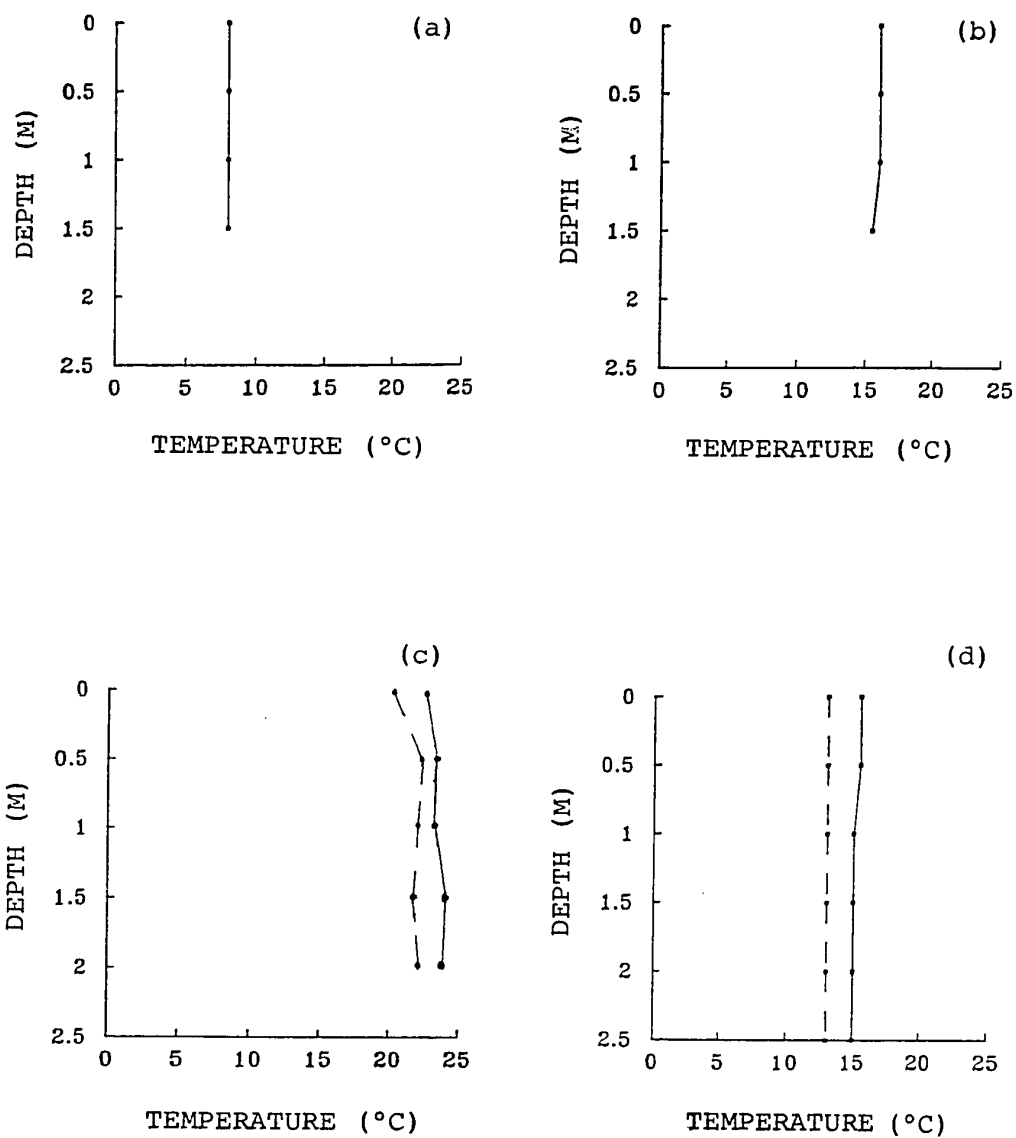
Figure 8a-d: Morning (dashed line) and afternoon (solid line) temperature profiles from Pond A9 for seasonal sampling dates (a) 22 Jan 1986; (b) 22 Mar 1986; (c) 28 Jun 1986; (d) 22 Nov 1986.

Table 1: Diurnal surface water temperatures at NS stations in Ponds A9 and A12 during seasonal samples.

	0600-0700	1000-1100	1500-1600	2100-2200	2400-0100
Pond A9					
Jul 19 1985	21	22	24	20	20
Nov 13 1985	16	-	-	15	16
Feb 07 1986	10	10	13	10	10
May 15 1986	15	17	21	21	18
Pond A12					
Jul 19 1985	20	21	24	22	21
Nov 13 1985	16	-	-	18	17
Feb 07 1986	8	11	12	11	10
May 15 1986	16	17	21	20	17

seasonally variable. In March 1986, temperature differences
between the surface and bottom were as great as 6 degrees C,
but in other seasons, and in shallower ponds, temperature
differences were no greater than 2 degrees C (Fig. 7a-d, 8a-
d).

pH

The pH in the salt ponds varied seasonally and with
pond type. Morning pH in the six ponds showed a negative
correlation with pond salinity (r= - 0.53, p < 0.05) (Fig.
9). The highest pHs were recorded in the two low salinity
ponds, with values typically 0.5 points greater than in the
high salinity ponds (Fig. 10 a-b). Minimum individual pH
was similar in all ponds, at 7.7-8.0, but the maximum values
varied with salinity. In the low salinity ponds, the highest
pH was 9.3-9.5, whereas in Ponds A12, A13, and A15 the
maximum level was only 8.7. Pond A11 was subject to sharp
salinity changes, and pH reached 9.0-9.2 when salinities
fell to 30 ppt.

Fluctuations in pH were often very dramatic, especially
in the low salinity ponds (Fig. 10a). The pH significantly
increased to 9.5 in Pond A9 in the May 1986, during a period
of maximum macroalgal cover. A general decline in pH
occurred in the summer with the introduction of low pH (pH =

27
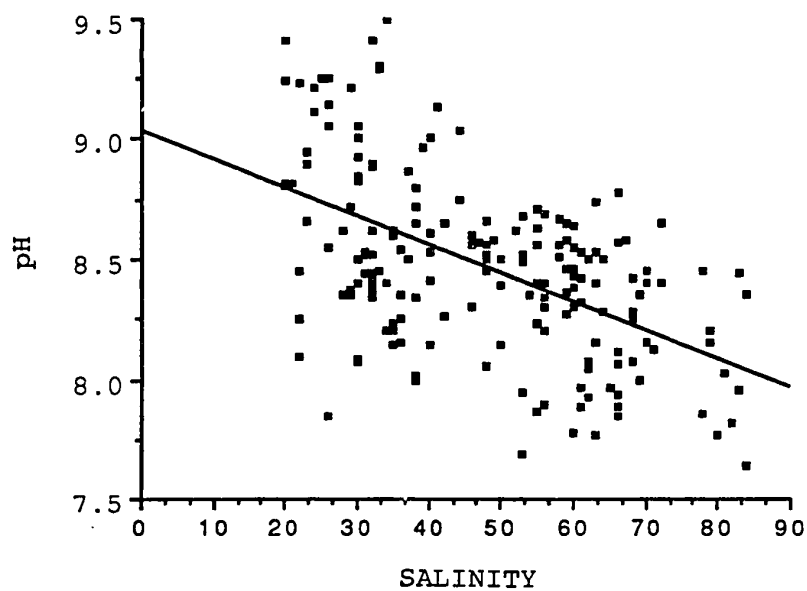
Figure 9: Morning NS station pH plotted against salinity from Alviso salt ponds from April 1985 to November 1986 (r = − 0.53).
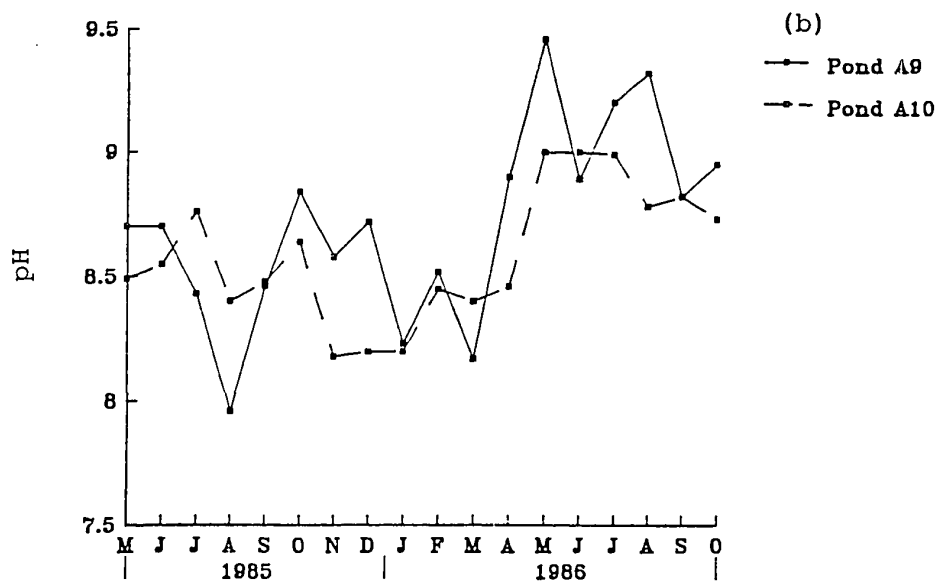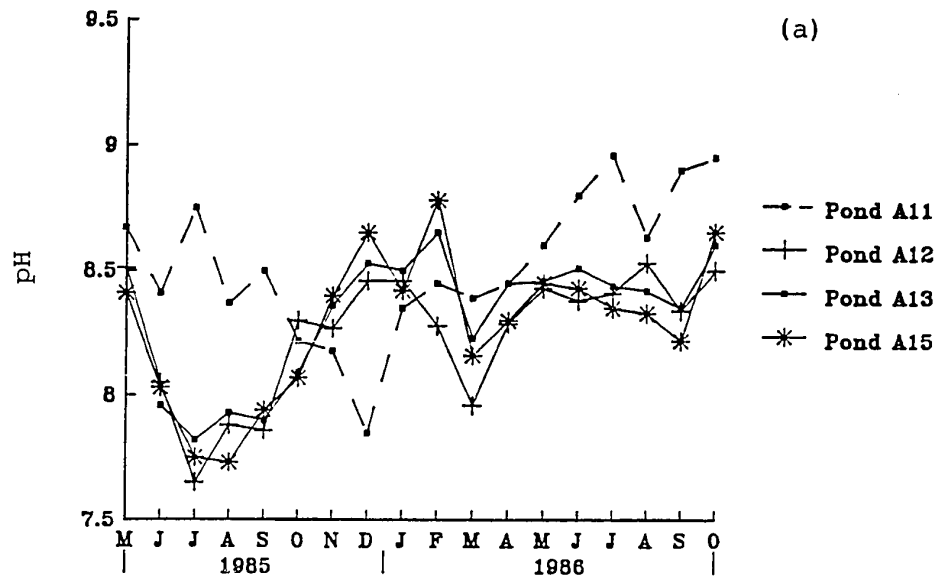
Figure 10a-b: Mean monthly morning pH measured at NS stations in Alviso salt ponds from May 1985 to October 1986.

29

8.0 - 8.4) water from Alviso Slough. In the high salinity
ponds pH also fluctuated widely, with the highest pH during
the summer of 1986, the period of lowest salinity (Fig. 10
b).

Multiple regression analyses demonstrated that pond
pH's were correlated with salinity, temperature, and
dissolved oxygen, although these correlations were not
consistent from pond to pond. In the high salinity ponds pH
was inversely correlated with salinity and positively
correlated with both temperature and dissolved oxygen. In
the low salinity ponds pH did not correlate with salinity,
temperature, or dissolved oxygen, but was probably most
affected by photosynthetic activity. During periods of
maximum algal abundance (spring 1986), pH increased.

Secchi depth/primary production

The results from monthly secchi depth measurements,
used here as an inverse index of phytoplankton abundance,
are presented in Fig. 11a-b. These results show higher
relative abundance of phytoplankton in the high salinity
salt ponds and wide seasonal variability in phytoplankton
abundance in the low salinity ponds.

Phytoplankton was the chief source of primary
productivity in the high salinity ponds (Ponds All to A15),
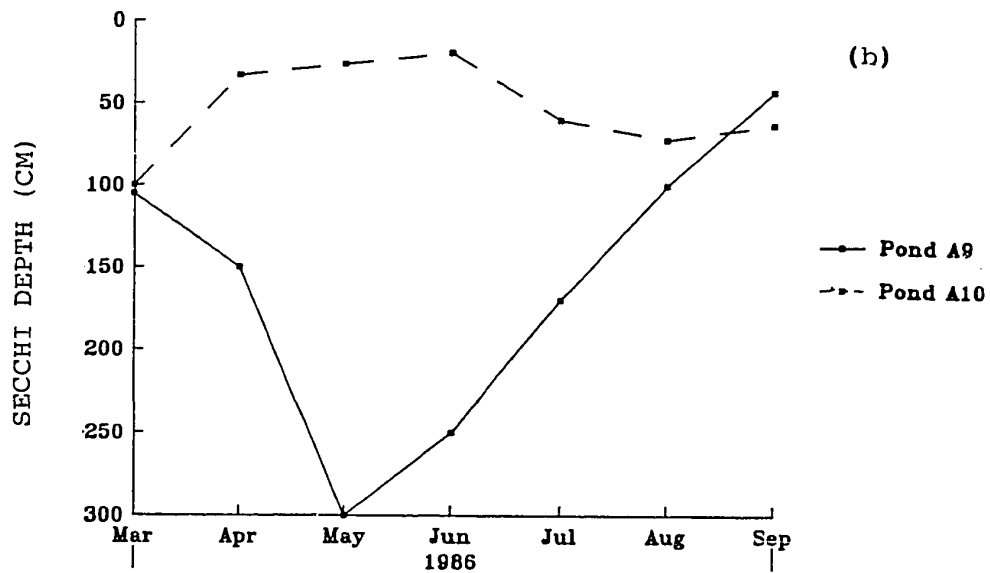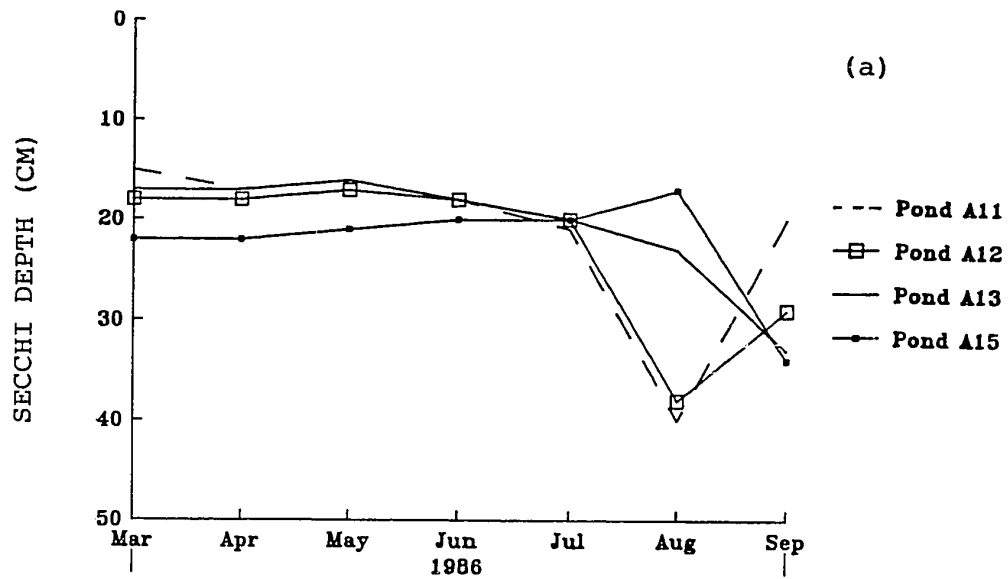
Figure 11a-b: Secchi depth for Alviso salt ponds from March to September 1986. Note scale change.

and were the only plants present when salinities exceeded 40 ppt. Although salinities were low enough during several months for macroalgae (i.e. Enteromorpha sp. and Ulva sp.) to grow, they never became a significant component of the algal community of Ponds A11 to A15. From March through July 1986, secchi depth measurements among the high salinity ponds were very similar, ranging from 15 to 22 cm (Fig. 11b). However, secchi depths increased sharply in Pond A11 and A12 in August, and in Ponds A13 and A15 in September following salinity declines produced by regulated water movements among ponds. Secchi depths in each of the four high salinity ponds (Ponds A11 to A15) were inversely correlated with salinity, indicating increasing phytoplankton abundance at high salinities (Fig. 12a-f and Fig. 13)

The low salinities of Ponds A9 and A10 were suitable for both phytoplankton and macroalgae, and both were present. Dominance by one group or the other depended on the season and pond water quality. Phytoplankton abundance in Pond A9 decreased from March to May 1986, then progressively increased until the conclusion of the study (Fig. 11a). Unlike the high salinity ponds, secchi depth in Pond A9 was negatively correlated with salinity ($r = - 0.91$) (Fig. 12e). Pond A10 showed increased phytoplankton abundance from March through June 1986 and declines

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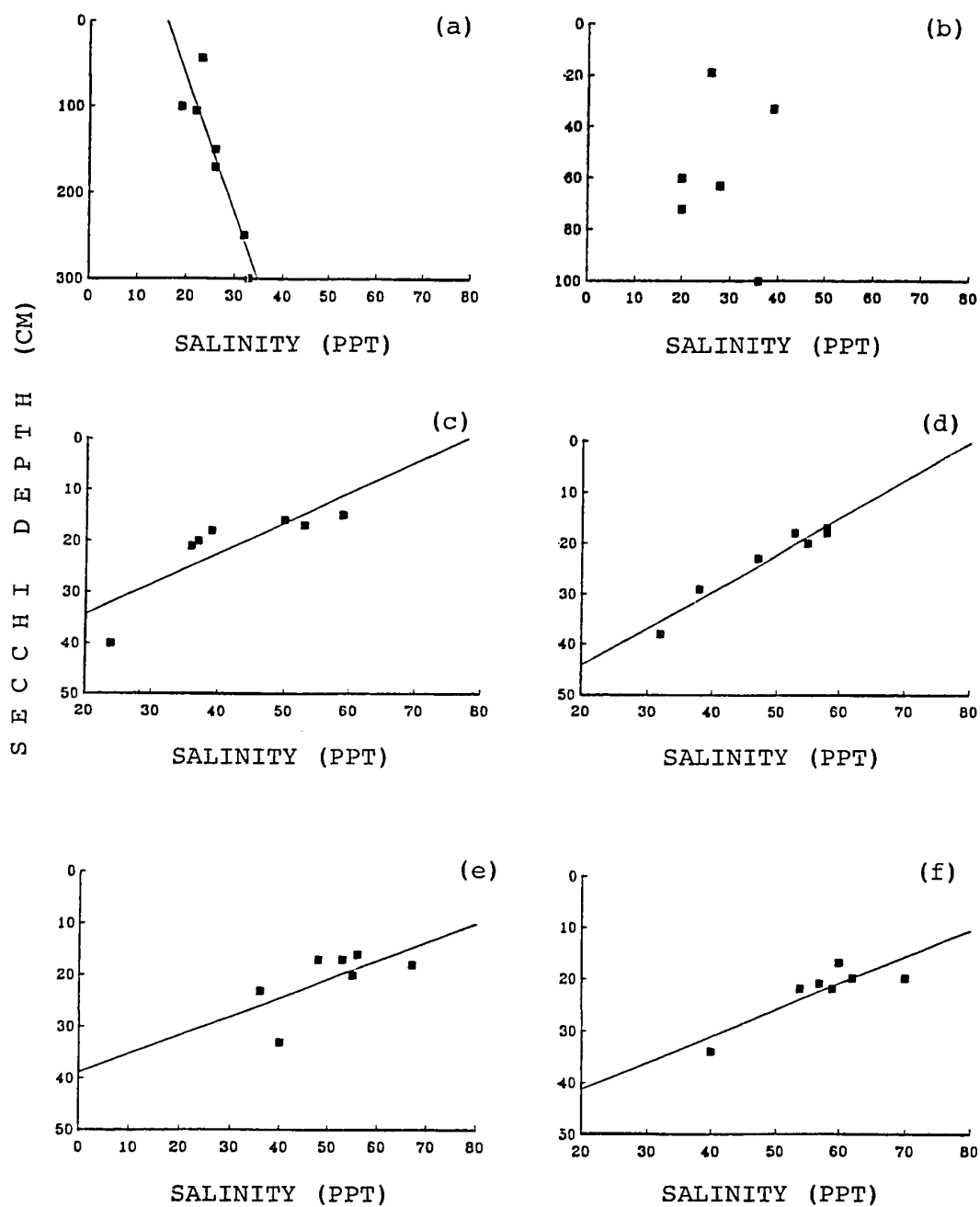
Figure 12a-f: Monthly secchi depths plotted versus salinity in Alviso salt ponds. (a) Pond A9; (b) Pond A10; (c) Pond A11; (d) Pond A12; (e) Pond A13; (f) Pond A15.

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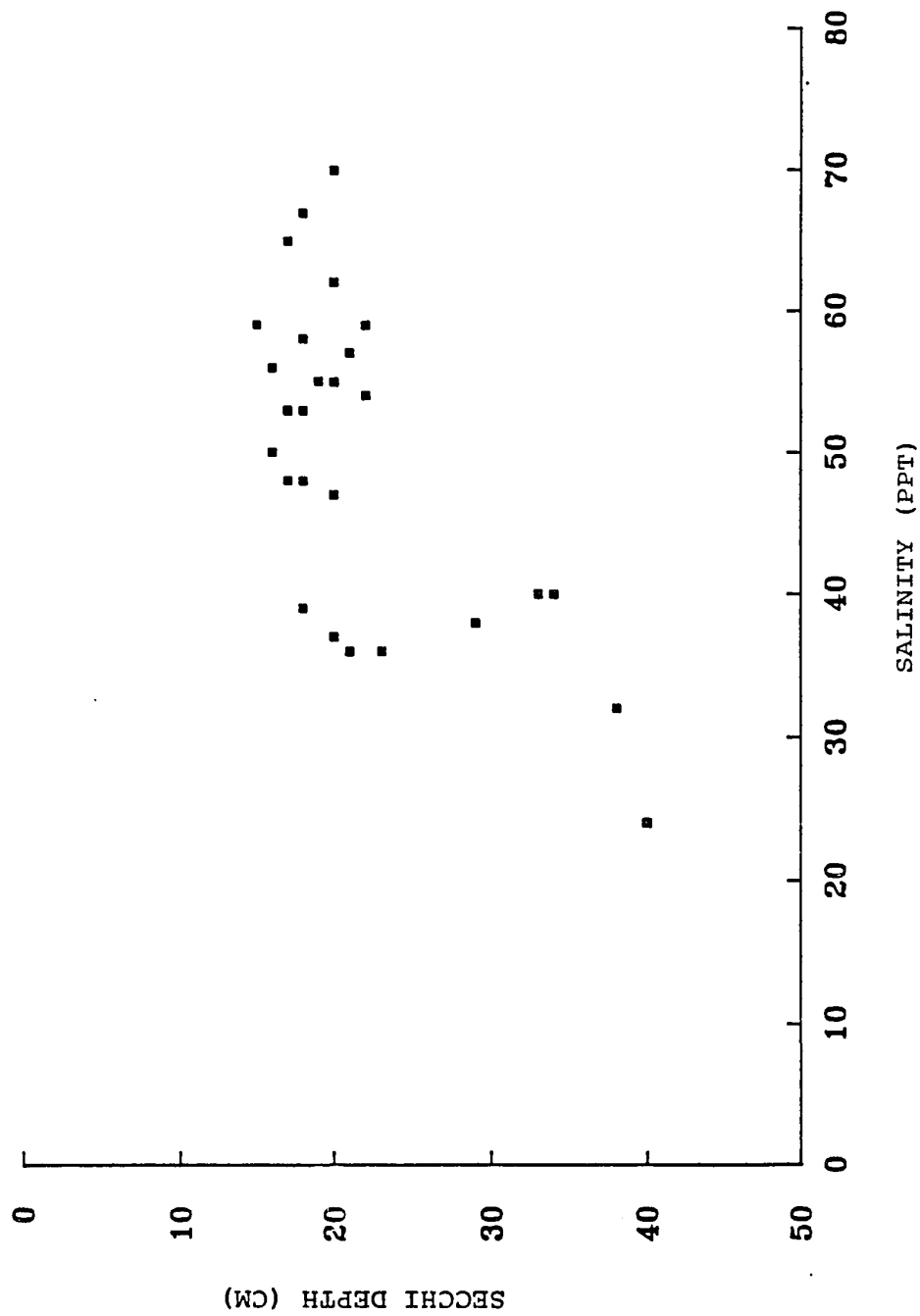
Figure 13: Secchi depth versus salinity in the four high salinity ponds (A11-A15) from March 1986 to November 1986.

thereafter; there was no correlation between salinity and phytoplankton.

Secchi depths in the two low salinity ponds, Pond A9 and A10, were usually much greater than in the high salinity ponds (Fig. 11a). Those differences and the seasonal changes in secchi depth and phytoplankton abundance may reflect competition between phytoplankton and macroalgae for light and nutrients. In the summer and fall of 1985, macroalgae, predominantly Enteromorpha, occupied as much as 60 percent of the surface of Pond A9 (Table 2). Macroalgae decreased to 25-30 percent cover in winter and early spring 1986, then increased again to 60 percent cover in June of 1986. This increase in surface macroalgal cover in 1986 was paralleled by a large increase in secchi depth, reflecting a sharp reduction in phytoplankton abundance (Fig. 11a). Macroalgal cover decreased from June to September 1986 (Table 2), and was accompanied by increased phytoplankton abundance and decreased secchi depths (Fig. 11a).

Enteromorpha was not as abundant in Pond A10 as in Pond A9 (Table 2). It was most common in Pond A10 during the fall and early winter of 1985-86, but died back in the winter and early spring of 1986, when the movement of water from Pond A11 back into Pond A10 drove salinities above 35 ppt. Phytoplankton then became the dominant plants through

35

Table 2: Estimated percent surface cover for
Enteromorpha in Ponds A9 and A1Ø, for August 1985
to September 1986.

Date		Pond A9	Pond A1Ø
August	1985	5Ø	25
October	1985	6Ø	15
January	1986	25	15
April	1986	3Ø	<1Ø
June	1986	6Ø	< 1
July	1986	25	< 1
September	1986	2Ø	5

the summer and fall, although their abundance declined in the late summer (Fig. 11a). Enteromorpha growth increased in September in the shallow waters of the pond (Table 2).

Dissolved oxygen

Mean northshore dissolved oxygen levels for the six ponds reflected the effect of temperature and salinity on maximum oxygen saturation. Levels were negatively correlated with salinity ($r = -0.7$, $p < 0.05$) in all six ponds, and with temperature in the four high salinity ponds ($r = -0.6$, $p < 0.05$). However, seasonal and daily variations in dissolved oxygen within ponds were large (Fig. 14a-d, Table 3) and reflected the additional effects of photosynthesis, wind action, and decomposition. Highest surface dissolved oxygen values in the high salinity ponds were during the winter months (Fig. 14b-d) and were probably caused by low pond water temperatures. Lowest levels were present in June and July 1985, with a range of 3.1 to 4.0 mg/l in the four ponds. In Pond A11, these low values were due to decaying vegetation transported by the inflows from Pond A10. These low values continued through the early fall of that year in Pond A11 and then occurred again in summer of 1986 (range 4.1-5.3 mg/l). In Ponds A12, A13, and A15, the dissolved oxygen decline in summer of 1985 was probably
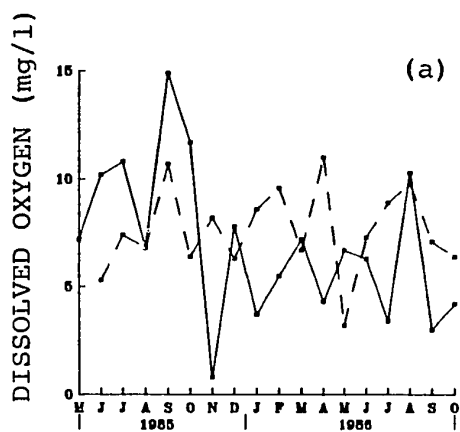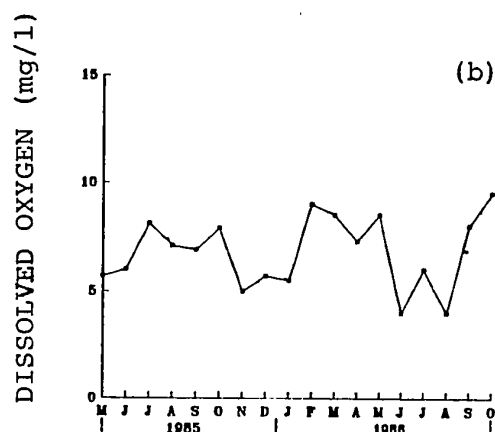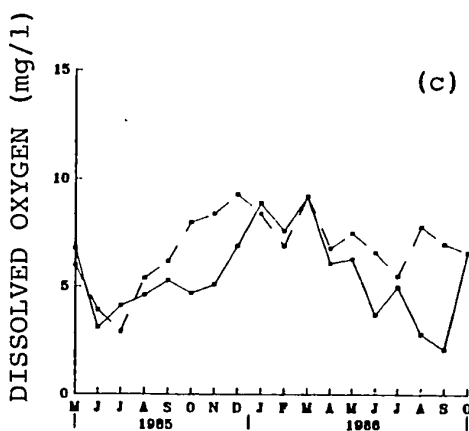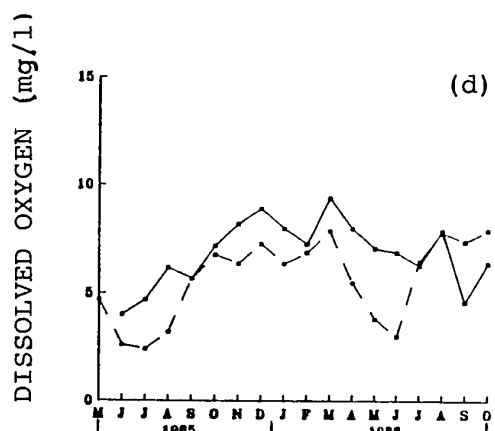
Figure 14a-d: Mean monthly dissolved oxygen levels measured at NS stations during morning hours in six salt ponds from May 1985 to october 1986. (a) Pond A9 (ns./ss); (b) Pond A10; (c) Ponds A11/A12; (d) Ponds A13/A15.

38

Table 3: Diurnal surface dissolved oxygen levels at NS stations in Ponds A9 and A12 during seasonal samples.

	0600-0700	1000-1100	1500-1600	2100-2200	2400-0100
Pond A9					
Jul 19 1985	7.8	8.3	-	7.2	7.2
Nov 13 1985	7.2	8.0	11.6	8.3	8.6
Feb 07 1986	7.8	11.0	13.0	12.0	9.0
May 15 1986	2.3	5.2	12.2	11.0	4.5
Pond A12					
Jul 19 1985	3.5	5.6	-	7.7	5.5
Nov 13 1985	9.9	10.0	11.9	11.0	11.0
Feb 07 1986	9.9	10.8	8.0	11.0	13.0
May 15 1986	7.5	8.7	13.0	7.9	7.1

39

due to very high salinities. In summer 1986, when salinities in Ponds A12 and A13 were much lower, no dissolved oxygen decline occurred; however, in Pond A15 salinity reached 70 ppt and dissolved oxygen dropped to as low as 3.0 mg/l.

In the low salinity ponds there were no significant correlations of dissolved oxygen with either salinity or temperature. However, decomposition and primary production did affect dissolved oxygen. In Pond A9, morning dissolved oxygen levels at the southshore site were generally high (range 7.0-14.9 mg/l) except for May of 1986, when a local die-back of macroalgae near the southshore sharply reduced dissolved oxygen levels to 3.3 mg/l (Fig. 14a). At the northshore site dissolved oxygen levels sharply dropped in November 1985 to less than 1 mg/l following the die-back of macroalgae near that shore (Fig. 14a).

Water column dissolved oxygen stratification differed seasonally and among ponds, but bottom waters in all ponds were usually hypoxic (<2 mg/l) or anoxic (Fig. 15-16). In March 1986, afternoon dissolved oxygen concentrations in high salinity ponds were supersaturated (> 8 mg/l) in the upper one meter, but hypoxic (< 2 mg/l) towards the bottom (Fig. 15b). In June 1986, oxygen stratification in the high salinity ponds became more extreme, and oxygen was saturated

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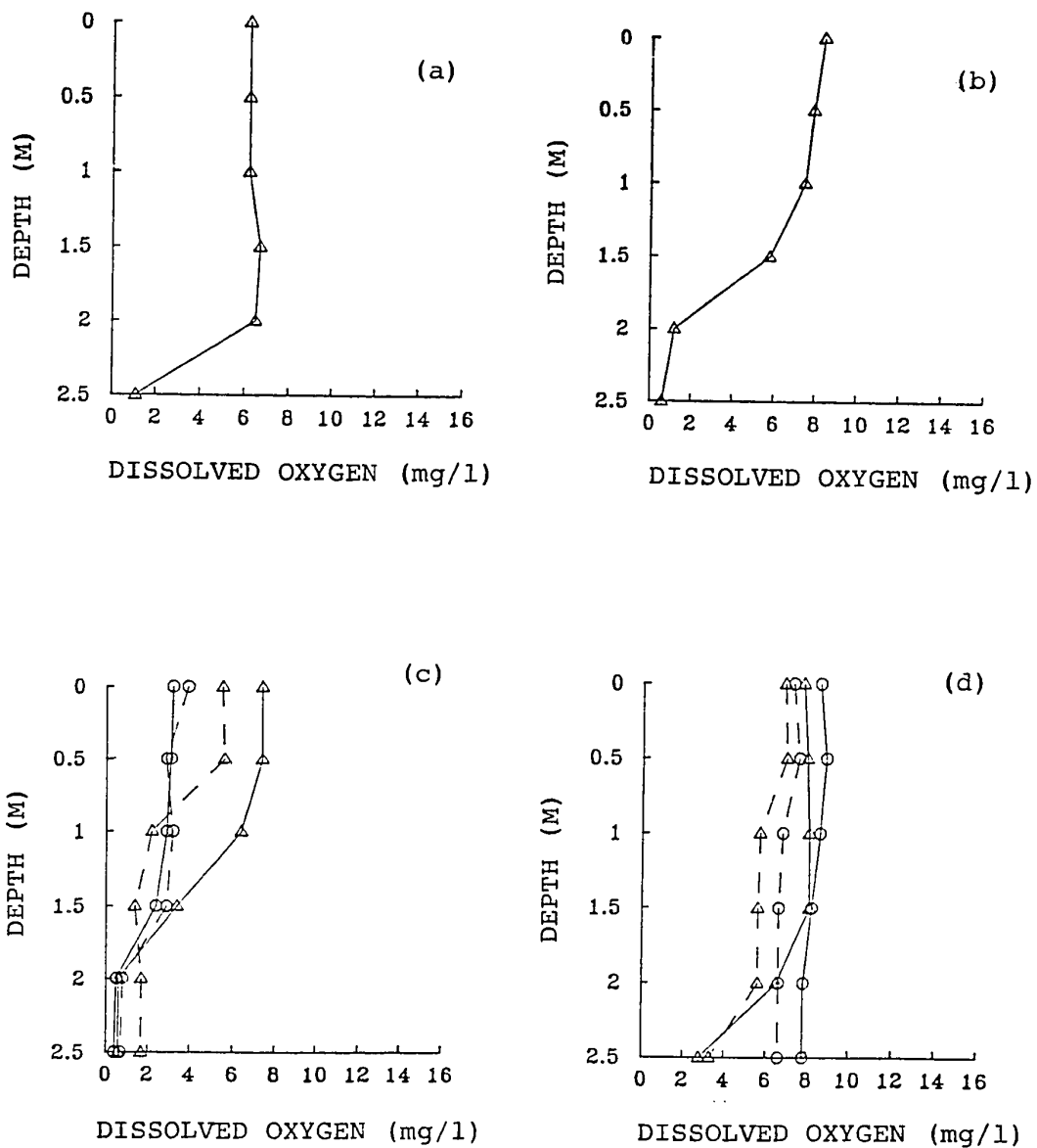
Figure 15a-d: Morning (dashed line) and afternoon (solid line) dissolved oxygen profiles from Pond A13 for seasonal sampling dates. (a) 22 Jan 1986; (b) 22 Mar 1986; (c) 28 Jun 1986; (d) 22 Nov 1986. NS stations (o) and SS stations (Δ).

41
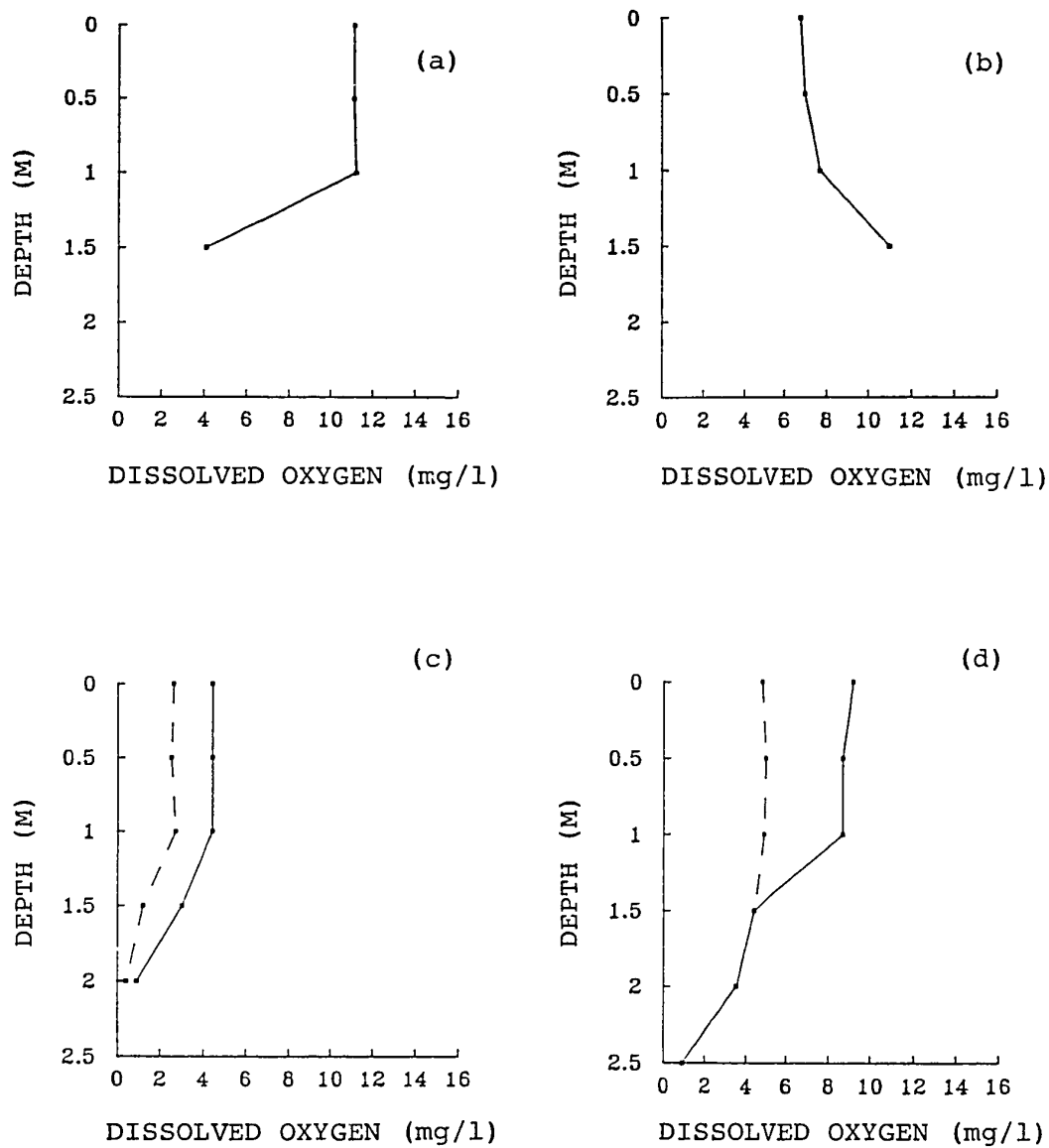
Figure 16a-d: Morning (dashed line) and afternoon (solid line)
dissolved oxygen profiles from Pond A9 for seasonal sampling
dates. (a) 22 Jan 1986; (b) 22 Mar 1986; (c) 28 Jun 1986; (d)
22 Nov 1986.

or supersaturated only in the upper 1/2 meter (Fig. 15c).
Differences between north and south shores measured then
were very pronounced. Lower values were recorded along the
northshore, where the levees provided protection from
northwesterly winds. Surface dissolved oxygen
concentrations during summer measurements in Pond A13 were
30 percent lower in morning at the northshore site than at
the southshore site (4.0 vs 5.5 mg/1) and 55 percent lower
in the afternoon (3.2 vs 7.4 mg/1). Dissolved oxygen
profiles in the November and January were similar to those
observed in March (Fig. 15 a, d).

Dissolved oxygen profiles in Pond A9 were much
different from the patterns measured in the high salinity
ponds, primarily because of extreme seasonal variability in
productivity and decomposition of macroalgae. In Pond A9,
high primary productivity in March, resulted in high
dissolved oxygen levels throughout the water column (Fig.
16b). These conditions persisted through the spring, but in
early June the die-back of macroalgae resulted in a period
of morning hypoxia and strong afternoon stratification (Fig.
16c). A phytoplankton bloom in the fall improved dissolved
oxygen conditions, but the effects of the earlier die-back
in macroalgae were still evident, as bottom waters remained
anoxic (<1 mg/1).

43

Dissolved oxygen fluctuated greatly during the day in Pond A9, especially during May (Table 3). These fluctuations were during periods of high algal abundance and high diurnal variation in respiration and photosynthesis.

Invertebrates

The distribution of invertebrates in the salt ponds varied spatially and temporally with salinity, dissolved oxygen, and algal growth. Species richness declined progressively with salinity, especially above 35 ppt. Seventeen species were collected from Pond A9, thirteen from Pond A10, five from Ponds A11 through A13, and two from Pond A15 (Table 4). Seasonal community level changes in the two low salinity ponds (Ponds A9 and A10) were pronounced (Table 5 and 6), and were primarily related to variations in the relative and absolute abundance of phytoplankton and macroalgae. The substrate in all six ponds was generally hard, often anoxic, and contained few invertebrates. Even the soft sediments, which were restricted to the dredged borrow pits, shorelines and remnant slough channels, contained few invertebrates because they were often covered with decaying vegetation and anoxic. In the low salinity ponds most of the benthic and epibenthic species relied on Enteromorpha as a substrate. Gammarid amphipods (i.e.

44

Table 4: Invertebrate species distribution in six Alviso salt evaporation ponds, 1985-86.

	A9	A1Ø	A11-A13	A15
		Distribution		
Cnidaria				
Actiniaria	X			
Mollusca				
Gemma gemma		X		
Ilyanassa obsoletus	X	X		
Tryonia imitator	X			
Annelida				
Nereis succinea	X	X		
Polydora ligni	X	X	X	
Tubificoides sp.	X	X		
Crustacea				
Anisogammarus confervicolus	X	X		
Artemia salina		X	X	X
Balanus sp.		X	X	
Copepoda	X	X	X	X
Corophium sp.	X	X	X	
Crangon spp.	X	X		
Hemigrapsus oregonensis	X	X		
Ostracoda	X			
Palaemon macrodactylus	X	X		
Sphaeroma quoyana	X			
Insecta				
Trichocorixa reticulata	X	X	X	

45

Table 5: Seasonal patterns of abundance for invertebrate species collected from Pond A9. r = rare; u = uncommon; c = common; a = abundant.

	Distribution				
	Fall	Winter	Spring	Summer	Fall
Cnidaria					
Actiniaria	-	-	c	-	-
Annelida					
Nereis succinea	u	u	u	u	r
Polydora ligni	-	-	c	c	-
Tubificoides sp.	-	-	a	a	a
Mollusca					
Gemma gemma	-	-	c	-	-
Ilyanassa obsoletus	c	u	c	-	u
Tryonia imitator	-	-	-	-	c
Crustacea					
Anisogammarus confervicolus	a	u	a	r	r
Balanus sp.	-	-	c	-	-
Copepoda	-	-	-	c	c
Corophium sp.	a	u	a	r	r
Crangon spp.	u	u	u	u	u
Hemigrapsus oregonensis	c	u	c	r	-
Ostracoda	-	-	c	-	-
Palaemon macrodactylus	c	u	c	u	u
Sphaeroma quoyana	c	c	c	c	-
Insecta					
Trichocorixa reticulata	-	-	u	-	-

46

Table 6: Seasonal patterns of abundance for invertebrate species collected from Pond Al0. r = rare; u = uncommon; c = common; a = abundant.

| | Distribution | | | | |
	Fall	Winter	Spring	Summer	Fall
Annelida					
Nereis succinea	–	–	–	–	u
Polydora ligni	–	–	a	–	–
Tubificoides sp.	–	–	a	a	–
Mollusca					
Ilyanassa obsoletus	c	u	c	–	u
Crustacea					
Anisogammarus confervicolus	c	–	–	–	–
Artemia salina	–	–	r	r	–
Copepoda	–	c	c	u	–
Corophium sp.	c	–	c	–	–
Crangon spp.	u	u	u	u	u
Hemigrapsus oregonensis	u	–	–	–	–
Palaemon macrodactylus	u	–	–	–	–
Insecta					
Trichocorixa reticulata	–	–	u	–	–

Corophium sp. and _Anisogammarus_ _confervicolus_), spionid
polychaetes (_Polydora_ _ligni_) and oligochaetes (_Tubificoides_
sp.) were the most common invertebrates collected, although
the molluscs _Tryonia_ _imitator_ and _Gemma_ _gemma_, the
polychaete _Nereis_ _succinea_, and the decapods _Crangon_ spp.,
Palaemon _macrodactylus_, and _Hemigrapsis_ _oregonensis_ were
also collected.

In Pond A9, species richness and abundance was highest
in the late spring of 1986 (Table 5), when _Enteromorpha_
covered as much as 60 percent of the pond surface. By the
summer and early fall of 1986, diminished algal abundance
and low dissolved oxygen levels reduced both species
richness and densities. Amphipod densities (_Corophium_ sp.
and _Anisogammarus_ _confervicolus_) which were high in the
spring, declined sharply in the summer. The oliogchaete,
Tubificoides sp., was most tolerant of poor water quality
and was abundant throughout the spring, summer, and fall of
1986. In the late summer and fall, a phytoplankton bloom in
Pond A9 was followed by an increase in copepod densities.
Changes in the benthic community in Pond A10 were also
related to fluctuations in water chemistry and algal
abundance. Replacement of macroalgae by phytoplankton in
the spring of 1986 was followed by a sharp decline in
amphipod and polychaete densities in the early summer (Table

48

6). _Tubificoides_ sp. was abundant in late spring and summer
in the decaying macroalgae. Both oligochaete and copepod
densities declined in the fall with reduced phytoplankton
abundance.

In the four high salinity ponds, the only common
benthic and epibenthic invertebrate species collected were
the polychaete _Polydora ligni_ and waterboatmen (_Trichocorixa
reticulata_). _Polydora_ was collected in shoreline sediments,
at high densities in Ponds A11, A12, and A13 at salinities
as high as 65 ppt. Waterboatmen, which are epibenthic, but
swim in the water column, were collected in low numbers in
plankton surveys of all six ponds and at all salinities.

When salinities dropped to sea water concentrations,
other species were also collected from Ponds A11 through
A15. _Corophium_ amphipods were abundant in the late summer
and fall of 1986 in Pond A11 near the intake from Pond A10,
while barnacles (_Balanus_ sp.) were found attached in large
numbers to the max-min thermometers in Ponds A11, A12, and
A13 during summer of 1986.

Zooplankton was the most abundant invertebrate group
in the high salinity ponds during all seasons, but was only
a seasonally important component in the low salinity ponds.
The most common zooplankton species were brine shrimp
(_Artemia salina_) and calanoid copepods, including

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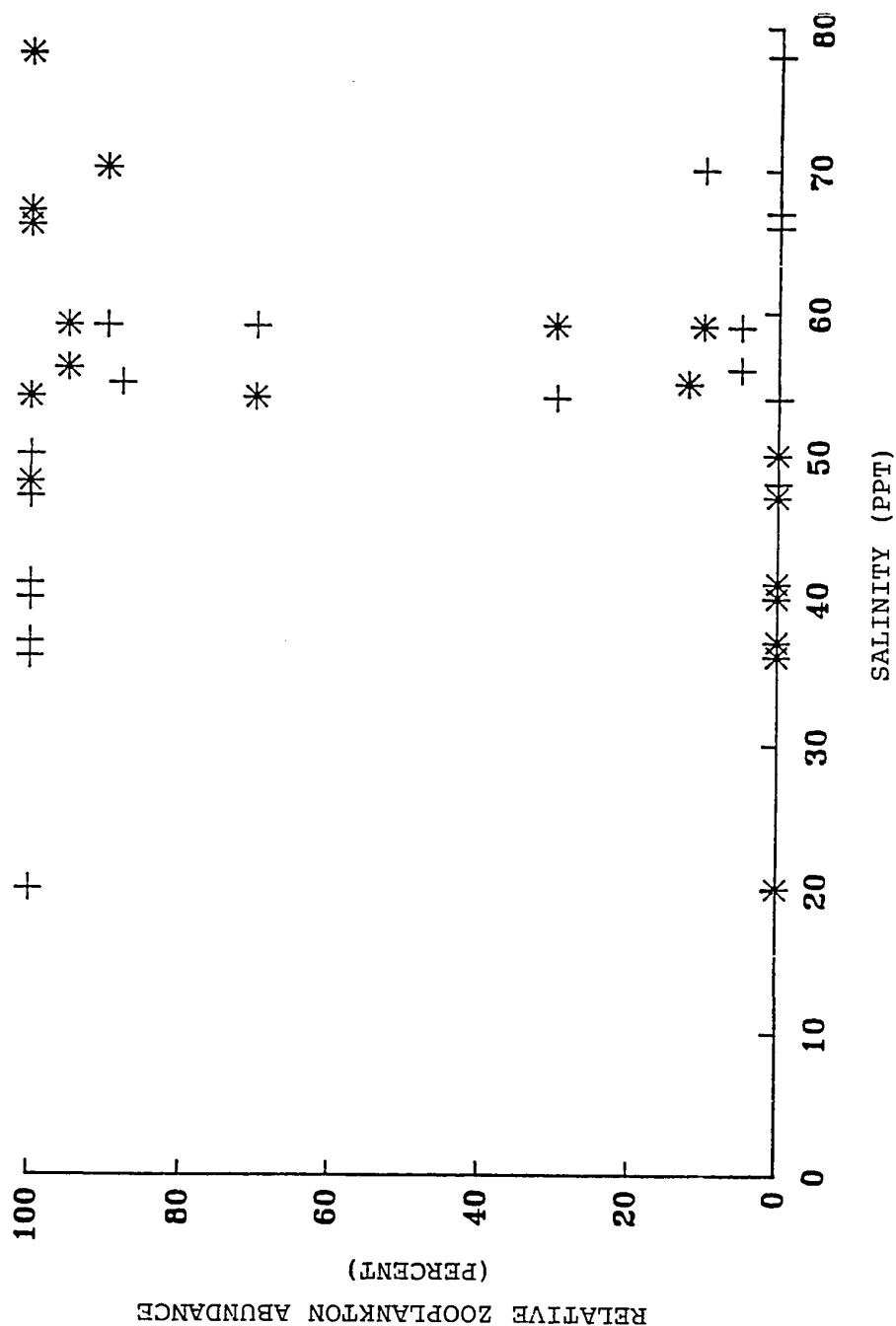
Figure 17: Relative abundance of _Artemia salina_ (*) and copepods (+) at different salinities in Alviso salt ponds between January 1986 to November 1986.

RELATIVE ZOOPLANKTON ABUNDANCE
(PERCENT)

SALINITY (PPT)

Table 7: Mean zooplankton biomass (g, dry wt.) and relative abundance of brine shrimp (Artemia salina) collected in surface plankton tows at NS stations in Alviso salt evaporation ponds. (n=2 for each mean, except *, where only one sample was taken).

	January		March		July		November		Pond mean	
	x + sd	%Artemia	x + sd	%Artemia	x + sd	%Artemia	x + sd	%Artemia	mean	%Artemia
A9	0.0	0	0.0	0	0.03+0.0	0	0.44+0.07	0	0.12	0
A10	0.0	0	0.23+0.03	0	0.06+0.01	0	0.0	0	0.07	0
A11	0.16+0.0	99	0.71+0.03	4	1.20+0.0	1	0.03+0.0	1	0.53	26
A12	0.27*	12	2.50+0.00	55	0.70+0.06	1	0.06+0.0	1	0.88	17
A13	0.32*	68	0.15+0.01	1	0.04+0.01	1	0.03+0.0	1	0.14	31
A15	0.51+0.1	100	3.10*	84	8.10+1.30	100	0.03+0.0	1	2.91	71
season mean	0.21	70	1.15	29	1.70	17	0.10	1	0.78	24

<u>Pseudodiaptomus</u> <u>euryhalinus</u>. The relative importance of these species varied with salinity (Fig. 17). At salinities greater than 60 ppt, brine shrimp were the predominant species, whereas at salinities below 45 ppt, copepods predominated. Between 45 and 60 ppt, neither species was predictably dominant.

Biomass estimates and species composition of zooplankton collected in the six salt ponds varied seasonally (Table 7). Zooplankton densities were generally highest in the high salinity ponds. In the four high salinity ponds zooplankton were most abundant in July 1986 and were least abundant in the early fall of 1986 when secchi depths were high, reflecting low phytoplankton abundance. Copepods were collected in A10 in the winter of 1985-86 and increased through the spring and summer of 1986. In Pond A9, copepods were not collected in the spring of 1986, but became increasingly common in the late summer following a summer phytoplankton bloom.

Fish

Over 12,000 fish of fifteen species were collected in the six Alviso salt ponds between August 1985 and November 1986 (Table 8). Topsmelt and long-jawed mudsucker were the most widespread species and had spawning populations in all

TABLE 8: Distribution and status of fish species collected in Alviso salt evaporation ponds, 1985-86. Pond (salinity range in ppt). R= resident population; S= seasonal population; J= juvenile only.

	POND					
Species	A9 (22-40)	A10 (22-40)	A11 (23-84)	A12 (30-66)	A13 (35-67)	A15 (40-83)
Topsmelt						
(Atherinops affinis)	R	R	R	R	R	R
Longjawed mudsucker						
(Gillichthys mirabilis)	R	R	R	R	R	R
Threespine stickleback						
(Gasterosteus aculeatus)	R	R	S	S	S	S
Rainwater killifish						
(Lucania parva)	R	R	S	S	S	S
Yellowfin goby						
(Acanthogobius flavimanus)	R	R	S	S	S	S
Pacific staghorn sculpin						
(Leptocottus armatus)	R	R	SJ	SJ	SJ	SJ
Bat ray						
(Myliobatis californica)	S	S				
Leopard shark						
(Triakis semifasciata)	S	S				
Northern anchovy						
(Engraulis mordax)	S	S				
Bay pipefish						
(Syngnathus leptorhynchus)	S	S				
Bay goby						
(Lepidogobius lepidus)	S	S				
Shiner surfperch						
(Cymatogaster aggregata)	S	S				
Starry flounder						
(Platichthys stellatus)	S	S				
Striped bass						
(Morone saxatilis)	S					
English sole						
(Parophrys vetulus)	S					

six ponds. Yellowfin goby (<u>Acanthogobius</u> <u>flavimanus</u>),
three-spined stickleback (<u>Gasterosteus</u> <u>aculeatus</u>), rainwater
killifish (<u>Lucania</u> <u>parva</u>), and Pacific staghorn sculpin
(<u>Leptocottus</u> <u>armatus</u>) also were present in all six ponds,
but regularly reproduced only in the low salinity ponds
(Pond A9 and A10). The remaining nine species occurred
irregularly as immigrants from the Bay and were found only
in salinities below 35 ppt. Several of these non-resident
species were present in Ponds A9 and A10 until the summer of
1986, but disappeared when dissolved oxygen conditions
deteriorated.

Seasonal changes in species composition within the high
salinity ponds were usually related to salinity. Most
species were not found at salinities above 35-40 ppt. In
the low salinity ponds, species composition also changed,
but in response to poor summer water quality.

Topsmelt

Seasonal topsmelt gill net results for the six ponds
are shown in Table 9. Topsmelt were collected in all ponds
to salinities as high as 85 ppt, whereas gravid females and
young fish were collected only to 70-75 ppt. There were
similar strong seasonal changes in catch rates in both high
and low salinity ponds, with catch per unit effort in 1986

54

Table 9: Catch per unit effort (mean ± S.D.) for the four most common fish species collected in 24 hour gill net surveys from Alviso salt ponds from fall 1985 to fall 1986.

		1985		Spring	1986	
		Fall	Winter		Summer	Fall
Topsmelt	A9/A10	22.3+14.2	0.0	13.4+14.0	22.9+16.1	592.0+405.0
	A11-A15	6.6+8.6	3.7+5.3	35.4+20.9	60.6+90.4	302.0+133.0
Longjawed mudsucker	A9/A10	0.8+0.9	0.1+0.4	0.0	0.6+0.8	5.3+2.9
	A11-A15	4.7+6.9	0.6+0.7	2.1+1.5	6.3+7.7	4.0+3.7
Yellowfin goby	A9/A10	13.3+7.3	3.4+4.0	0.0	1.5+2.5	4.5+2.1
	A11-A15	2.3+6.3	0.0	0.4+0.6	0.0	0.5+0.7
Staghorn sculpin	A9/A10	12.9+14.4	3.4+4.4	70.7+138.1	2.2+4.4	4.4+3.1
	A11-A15	0.3+0.7	0.0	0.1+0.1	0.0	0.0
no. of surveys	A9/A10	6	10	8	6	3
	A11-A15	6	7	3	7	3

increasing from winter through the following fall. Mean
lengths of fish collected by gill net increased from spring
through summer 1986 and decreased again in fall 1986 (Table
10). Mean size of topsmelt in high salinity ponds was less
than in the low salinity ponds in all seasons (Table 11).

The spawning season of topsmelt in the salt ponds was
determined from fish captured in Ponds A11 to A15. These
fish were less likely to include immigrants from San
Francisco Bay than topsmelt captured in the two low salinity
ponds (Ponds A9 and A10). Based on measurements of gonad
volume and egg size in fish collected from the high salinity
ponds, the spawning season for topsmelt in the ponds
extended from February through September, with a peak
between March and July (Table 11). Several fish collected
in February contained a small number of mature eggs, and the
proportion increased through July. Fish containing ripe or
mature eggs were still collected as late as September, but
October fish contained only immature eggs. Larval and
juvenile topsmelt (<30 mm) were collected in the months of
March and August. However, larval fish were also collected
in December 1985 and January 1986, suggesting that the
spawning season may have been more protracted than the gonad
data indicated.

Female topsmelt reached sexual maturity at

Table 10: Standard lengths (mean $\pm$ S.D.) of topsmelt collected by gill net in low and high salinity ponds from fall 1985 to fall 1986.

	Fall	Winter	Spring	Summer	Fall
Ponds A9/A10	114.8$\pm$9.3	-	114.7$\pm$6.7	121.2$\pm$6.7	108.5$\pm$6.2
n	67		21	25	114
Ponds A11/A15	104.4$\pm$9.3	105.9$\pm$2.3	105.9$\pm$5.9	113.2$\pm$6.7	105.5$\pm$5.2
n	32	8	177	114	140

Table 11: Measurements of reproductive maturity in adult topsmelt (> 100 mm) collected from four high salinity ponds between February 1986 and October 1986. Percent volume-gonads is the gonad volume as percent of the total fish volume. Egg maturity was based on measurements of egg diameter, with 1 = immature eggs, 2 = mature eggs, 3 = spent (after Schultz, 1933).

	n	volume-gonads	egg maturity
February	10	17.3 + 8.3	1.4 + 0.3
March	23	17.9 + 7.5	1.7 + 0.4
May	9	16.9 + 6.3	
June	14	17.3 + 8.3	1.8 + 0.4
July	6	25.6 + 15.0	2.0 + 0.0
September	2	10.4 + 4.7	2.3 + 0.4
October	10	0.0	3.0 + 0.0

approximately 100-110 mm SL, while males matured at

approximately 90-100 mm. The life-span of the resident

topsmelt, based on length frequency data and scale aging,

was less than 2 years. Fish hatched in the spring grew to

90-100 mm by late fall, and some may have spawned by the end

of their first year. By the spring of their second year all

of the fish were mature. At the end of their second summer

topsmelt attained lengths of 120-130 mm. No topsmelt longer

than 130 mm were collected in the high salinity ponds.

Food habits of topsmelt varied substantially with pond

and season (Table 12), but in general food selection

reflected the relative abundance of available prey. In the

high salinity ponds topsmelt consumed brine shrimp,

waterboatmen, and copepods (Table 12). Waterboatmen and

brine shrimp were the principal prey during periods when

salinities were high (i.e. the winter and spring), and

copepods were the principal prey when salinities were low

(i.e. summer and fall). Benthic species, such as Polydora

ligni and brine fly larvae, were not found in sampled

stomachs. In the low salinity ponds, the diet of topsmelt

varied with the changes in the structure of the algal and

invertebrate communities. Gammarid amphipods (i.e.

Corophium sp.) were the primary prey during macroalgal

blooms, whereas planktonic algae and copepods were fed on

59

Table 12: Diet of topsmelt (Atherinops affinis) from four high salinity ponds, and the relative availability of prey species (prey av.) determined from plankton surveys.

	Winter 1985–86, n = 23				Spring 1986, n = 13			
	%freq	%number	%vol	prey av.	%freq	%number	%vol	prey av.
Brine shrimp	87	76	76	100	55	44	33	66
Copepoda	0	0	0	0	19	17	15	33
Waterboatmen	21	24	24	–	74	39	38	–
Mean std. length (mm)	93				93			

	Summer 1986, n = 22				Fall 1986, n = 11			
	%freq	%number	%vol	prey av.	%freq	%number	%vol	prey av.
Brine shrimp	68	26	39	25	36	3	8	1
Copepoda	68	56	42	75	82	86	67	99
Waterboatmen	42	15	18	–	82	11	17	–
Mean std. length (mm)	92				99			

60

during phytoplankton blooms.

Longjawed mudsucker

Longjawed mudsuckers were collected in all six ponds at all salinities. Like topsmelt, mudsucker experienced seasonal variations in abundance (Table 9). Highest longjawed mudsucker catches were during the summer and fall, while very few individuals were collected during the winter. Gill net catches were usually greater in the high salinity ponds than in the low salinity ponds, except for the fall of 1986 (Table 9).

The spawning season for longjawed mudsucker, based upon length frequency distributions of fish collected from Ponds A11 to A15, was estimated to extend from November through June. Most reproduction appeared to be concentrated in February-March. Larval fish (<10mm) were first collected in early December 1985, but highest densities were found in March 1986 in Ponds A12 and A13. Longjawed mudsucker larvae were collected in every pond and at salinities up to 70 ppt.

Longjawed mudsucker grew to approximately 80-100 mm SL in their first year, and up to 120-140 mm by their second year. One year old fish had mature gonads. Very few individuals survived past their first year, and no fish older than two years were collected in the ponds.

61

Table 13: Diet of longjawed mudsucker (<u>Gillichthys mirabilis</u>) from four high salinity ponds, and the relative availability of prey species (prey av.) determined from plankton surveys.

	Winter 1985-86, n = 5				Spring 1986, n = 5			
	%freq	%number	%vol	prey av.	%freq	%number	%vol	prey av.
Brine shrimp	20	3	1	12	50	56	26	66
Copepoda	40	26	17	88	0	0	0	33
Waterboatmen	80	72	50	-	100	50	74	-
<u>Polydora ligni</u>	0	0	0	-	0	0	0	-
detritus	40		30	-	0	0	0	-
Mean std. length (mm)	78				89			

	Summer 1986, n = 13				Fall 1986, n = 5			
	%freq	%number	%vol	prey av.	%freq	%number	%vol	prey av.
Brine shrimp	100	60	55	1	0	0	0	1
Copepoda	8	1	1	99	33	20	5	99
Waterboatmen	23	13	13	-	83	50	35	-
<u>Polydora ligni</u>	8	5	5	-	33	20	5	-
detritus	8		7	-	50		50	-
Mean std. length (mm)	72				73			

A limited sample of longjawed mudsuckers (n = 5) collected from the low salinity ponds were found to have fed on polychaetes and amphipods. In the high salinity ponds (n = 29), they fed primarily on waterboatmen and brine shrimp (Table 13). Soft bodied species, such as Polydora ligni, were rare in stomachs, possibly reflecting their easier digestion. Copepods, despite their small size, were an important winter food item for adult mudsuckers. However, they were not utilized in spring, when brine shrimp were relatively abundant (Table 13).

Yellowfin goby

Yellowfin goby were commonly collected in Ponds A9 and A10 during the fall of 1985 and 1986, but decreased in numbers during the winter and spring of 1986 (Table 9). Yellowfin goby were collected in the higher salinity ponds, including one adult in Pond A13 during February 1986 at a salinity of 50 ppt, but they appeared to be rare in these ponds. Gravid females were collected in late winter 1986 in Pond A9, and larval goby were collected in early spring from Pond A9. Many of the individuals using the ponds were probably immigrants from the Bay, since numbers were low except for periods when the ponds were open to the Bay (June to November 1986). The ages of the yellowfin goby collected

63

ranged from 0 to 2 years old. No fish older than 2 years,
or longer than 160 mm SL, were collected. Yellowfin goby
was the only species collected that fed heavily on
polychaete and oligochaete worms in the low salinity ponds.
Their diet also included most other invertebrates and even
killifish. Yellowfin goby examined from the high salinity
ponds (n = 4), contained brine shrimp and juvenile yellowfin
goby.

Rainwater killifish

Rainwater killifish appeared to be permanent residents
in the low salinity Ponds A9 and A10, and at least seasonal
residents in the high salinity ponds. They were found in
salinities as high as 80 ppt, but were most abundant in beds
of Enteromorpha in Ponds A9 and A10. Along with three-
spined stickleback, they survived in Pond A9 in the summer
of 1986 when low dissolved oxygens and food densities
severely reduced or eliminated populations of other fish
species from the pond.

The presence of larval killifish in Pond A12 and A13
during March 1986 (the apparent spawning peak) indicated
spawning is possible at salinities of 55 ppt. The few
killifish examined (n = 7) fed exclusively on crustaceans.
At low salinities, they fed on amphipods, while at higher

64

salinities they fed on brine shrimp and copepods.

Three-spined stickleback

Three-spined stickleback were permanent residents in Ponds A9 and A10, and seasonal residents in the higher salinity ponds at salinities of up to 65 ppt. Their abundance was highest in the low salinity ponds and progressively decreased in the high salinity ponds. Although juvenile and adult three-spined stickleback were collected in the winter and spring in most ponds, they were most abundant after early June when Bay water was introduced into Pond A9.

The diet of three-spined stickleback (n = 7) was very similar to the killifish. In the low salinity ponds stickleback fed on the amphipods inhabiting the algal mats, whereas in the high salinity ponds they fed on brine shrimp and copepods.

Staghorn sculpin

Both adult and juvenile staghorn sculpin were present in the ponds. Juvenile fish (10-15 mm) were first collected by December 1985 and may have immigrated from the Bay or hatched within the ponds. By late spring staghorn sculpin, less than 100 mm SL, were the most abundant species

collected in Ponds A9 and A10. Although always most
abundant in these ponds, juvenile sculpin were tolerant of
high salinities and actively dispersed to all ponds (Table
9). They were collected from Pond A15 in late spring 1986
when the salinity was 65 ppt. However, by late summer they
had disappeared from the high salinity ponds despite the
fact that pond salinities dropped. They also became less
numerous in summer gill net surveys of low salinity ponds
(Ponds A9 and A10), before increasing again in the fall.

The diets of adult (n = 5) and juvenile staghorn
sculpin (n = 21) in the salt ponds were quite distinct.
Adults fed almost exclusively on large prey (i.e. killifish,
gobies, and Crangon spp.). Juvenile fish preyed on much
smaller food items, including polychaetes and large
amphipods in the low salinity ponds, and brine shrimp in the
high salinity ponds.

Non-residents

Eight species of non-residents were present in Pond A9
in the fall of 1985, but only juvenile leopard shark
(Triakis semifasciata), adult bay pipefish (Syngnathus
leptorhynchus), shiner surfperch (Cymatogaster aggregata),
and juvenile starry flounder (Platichthys stellatus) were
collected through late spring of 1986. Adult northern

66

anchovy (<u>Enraulis</u> <u>mordax</u>) were common in fall 1985 but
absent during the remainder of the study. Juvenile english
sole (<u>Parophrys</u> <u>vetulus</u>), adult bay goby (<u>Lepidogobius</u>
<u>lepidus</u>), and juvenile bat ray (<u>Myliobatis</u> <u>californica</u>) were
occasionally collected in fall 1985. Juvenile striped bass
(<u>Morone</u> <u>saxitalis</u>) (<150 mm SL) were collected only in fall
1986. None of these species was common in Pond A10, and
none was collected in either Pond A9 or A10 during the
summer of 1986 when dissolved oxygen levels were severely
depressed.

DISCUSSION

Environmental conditions in the low to moderate
salinity (20-85 ppt) salt evaporation ponds of south San
Francisco Bay differ substantially from those in the
surrounding Bay environment. Although seasonal temperature
ranges in these ponds are similar to those of the South Bay
(Aplin, 1967), the ponds show much greater seasonal and year
to year variability in dissolved oxygen, pH, and salinity.
Two types of pond environments exist among the six salt
ponds studied. These include the generally hyposaline or
brackish water habitats of Ponds A9 and A10 (20-40 ppt)
which supported many of the local South Bay fish species.
Factors which influenced community structure in these ponds
included immigration from the Bay, seasonal fluctuations in
relative and absolute abundance of phytoplankton and
macroalgae, dissolved oxygen levels, and to a lesser degree,
salinity. The generally hypersaline habitats of Ponds A11
through A15 provided the other habitat type. The high
salinity ponds were very productive for those few species of
fish (i.e. topsmelt and mudsucker) and invertebrates (i.e.
brine shrimp) which could survive in them, but they showed
strong seasonal fluctuations in productivity and composition
of less tolerant species.

Within the low salinity ponds (Ponds A9 and A10) salinity was not generally limiting since the range of salinities in these ponds overlaps with the range that estuarine organisms are exposed to in the South Bay (Aplin, 1967, Conomos, 1979). Immigration from the South Bay into these ponds is limited to those species of fish found in the surrounding Bay during the months when the ponds are open to tidal flow, generally May through October. In the present study, fifteen fish species appeared to enter the ponds from the Bay, and eight to ten of these appeared to sustain populations in the ponds only with this immigration. In Carpelan's earlier study (1957), he reported few migrants, apparently because South Bay water quality was quite poor then and South Bay fish rare (Regional Water Pollution Control Board, 1957).

The green macroalga, Enteromorpha sp., was an important food resource and micro-habitat for both fish and their invertebrate prey in the low salinity salt ponds. However, the die-back of macroalgae during the winter and spring of 1986 brought on widespread loss or reduction of shelter and food. These losses and low dissolved oxygen levels produced by the decomposing algae greatly reduced invertebrate and fish abundances and delayed their recovery until late summer and fall.

The mechanisms for the changes in the source of primary productivity in Ponds A9 and A10 are not fully understood, although it does appear that in each pond the causes were different. In Pond A10, the late winter 1986 die-back of macroalgae coincided with the influx of turbid, hypersaline water from Pond A11. Increased salinity or plankton-derived turbidity may have suppressed macroalgal production. Bio-turbidity and nutrient uptake by the phytoplankton appeared to have excluded Enteromorpha from the pond for most of the following summer. In Pond A9, the summer die-back of macroalgae coincided with high pH and salinity levels that peaked at 10.0 and 35 ppt, respectively. The rate of photosynthesis by Enteromorpha diminishes at higher salinities (Josselyn and Shellem, 1982) and at high pH (Jollife and Treguna, 1970). At high pH the primary source of carbon available to plants is as HCO_3 and CO_3 (Olausson, 1980). Enteromorpha can utilize neither as a carbon source (Howe, 1937; Jollife and Treguna, 1970). Increased turbidity in Pond A9 and A10 may also have been a factor in suppressing macroalgal growth.

Blooms of Enteromorpha are most common in shallow, warm, nutrient rich and moderately saline (10-20 ppt) waters of San Francisco Bay (Josselyn and West, 1985). However, pond management practices, and the non-tidal nature of the

70

salt pond habitats, can turn seasonal cycles into annual crises. In tidal systems, decomposing algae can be washed off mudflats by the tides, and fish can avoid areas of low dissolved oxygen. In the ponds, decomposing algae accumulates on the bottom and fish are trapped in areas of oxygen depletion and invertebrate scarcity. Salt pond fish communities may annually be subjected to dissolved oxygen and food source stresses of the type which caused the community level changes observed in Ponds A9 and A10 in 1986. However, the severity of these changes may vary annually. Because of this variation, the species composition of fishes in these low salinity ponds is also variable. The makeup of the fish community will reflect the colonizing species pool found in the surrounding Bay during the recovery.

Macroalgae were rarely found in the high salinity ponds and were never abundant, apparently because of high salinities and high bio-turbidities. Macroalgae were only present in Ponds A11 and A12 when salinities were low (23-30 ppt) and were confined to the shallow pond edges where they could not be shaded by phytoplankton. The absence of macroalgae eliminated the episodic crashes in primary productivity that occurred in the low salinity ponds, where macroalgae were a dominant source of production.

In this study phytoplankton abundance was strongly related to salinity. Changes in salinity, especially in the 35-40 ppt range, led to reduced algal abundance in the ponds. Although these changes occurred in the summer, it is not likely that high water temperatures caused these declines. Pond temperatures are well within the tolerance range of pond phytoplankton (Gibor, 1956). The salinity range closely matches the range where Gibor (1956) (Fig. 18) found changes in relative growth rates of salt pond phytoplankton species. This suggests that the reduced production may be due to species shifts in the phytoplankton community.

Hypoxia of subsurface waters was encountered in both the low and high salinity ponds. Dissolved oxygen stratification often forced distributional changes in the fish and invertebrate species. During those periods of extreme hypoxia in the ponds (i.e., summer) fish and invertebrates were forced towards the oxygenated surface layer, where they became much more vulnerable to avian predation. Feeding aggregations in the ponds by terns, herons, pelicans, and cormorants were observed almost exclusively during the summer.

The absence of brine shrimp from salinities below 50 ppt may reflect the efficiency of fish predators,
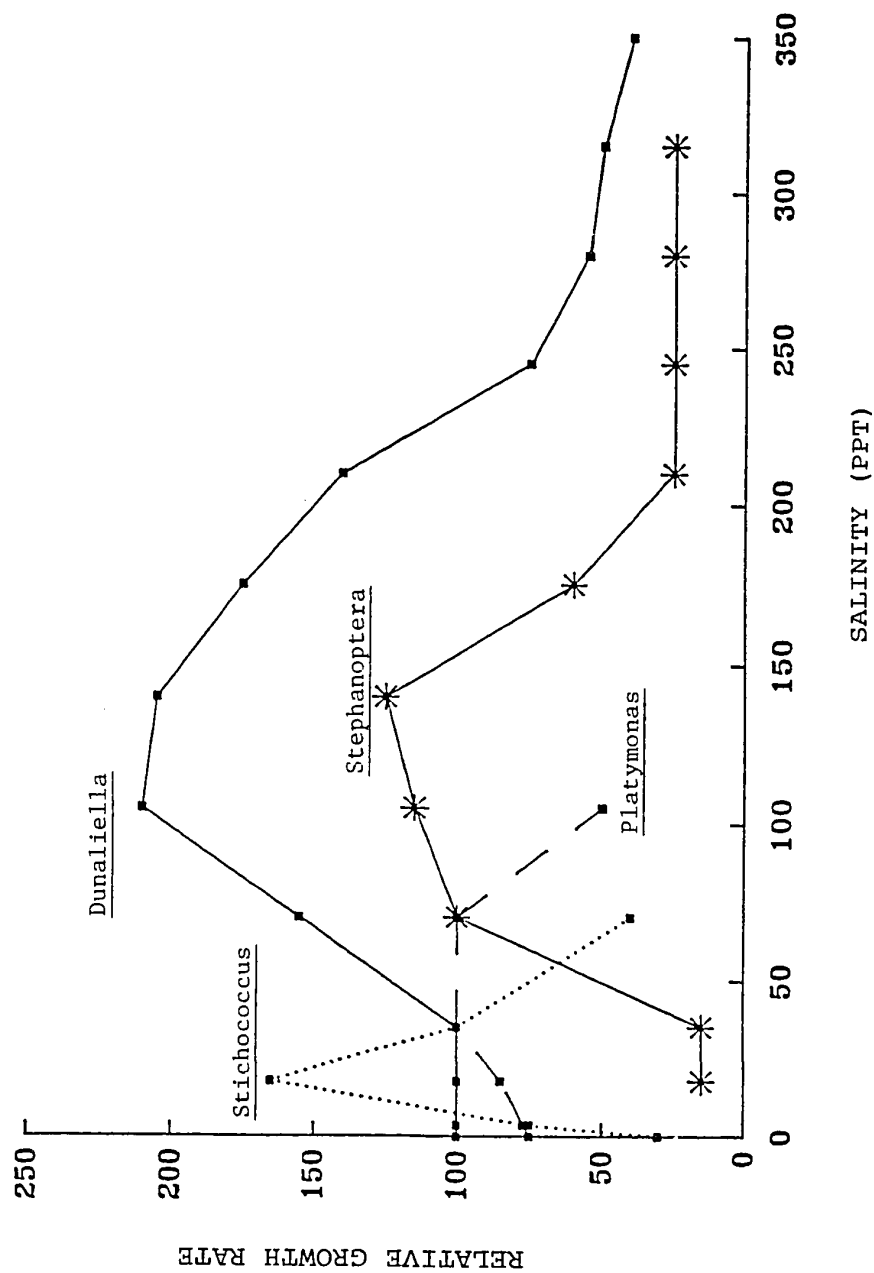
Figure 18: Relative growth rates in culture of predominant salt pond phytoplankton at different salinities. Data from Gibor (1956).

73

competition with other zooplankton, or the scarcity of a suitable phytoplankton food source. In this study phytoplankton abundance was often reduced at low salinities. In addition, the most common phytoplankton of salinities below 40 ppt, Sticchococcus bacillaris (Carpelan, 1957), can not be digested by brine shrimp (Carpelan, 1964).

The periodic environmental stresses found in the salt ponds, which lead to dramatic changes in species composition in both low and high salinity pond habitats, favor fish species which are small, short-lived, opportunistic, and early spawners. Non-resident species included some adults, but most were represented by juveniles. These species are handicapped by an inability of certain life stages to cope with prevailing pond conditions or with periods of poor water quality. Juvenile fish may generally be more euryhaline than large fish, possibly because of changes in metabolic rates that occur with age (Kinne, 1964).

Most salt pond fish species spawned in their first or second year and did not survive longer than two years in the ponds. Although topsmelt, yellowfin goby, and mudsucker can live more than two years in San Francisco Bay (Schultz, 1933; Armor and Herrgesell, 1985), adults of these species were not abundant by the winter of their second year in the ponds. This suggests that late fall and winter may be

74

stressful to post-spawning adults. The same level of stress
does not develop for juvenile fish, since they survive the
winter to spawn in the subsequent spring and summer.
However, scales of juvenile topsmelt showed growth reduction
during their first summer and fall.

The opportunistic diet of salt pond fishes may be a
necessary strategy in the ponds. Topsmelt, for example,
feed predominantly on algae in estuaries (Moyle, 1976), but
in the ponds, where seasonal and spatial variability in prey
resources was common, the topsmelt diet included fish,
amphipods, copepods, and brine shrimp.

CONCLUSIONS AND RECOMMENDATIONS

Management of Alviso salt ponds for salt production has produced locally unique habitats, with fluctuating salinities, relatively stable water levels, and periods of low dissolved oxygen and high pH. These habitats are heavily utilized by many invertebrates, fish, and birds that prey on them. However, the rapid movement of water among ponds, and the seasonal closure to tidal action, which are characteristic of present salt pond management, reduce the value of the ponds as habitats. Rapid movement of water, and the resulting salinity changes, especially in the 30-40 ppt range, appear to trigger major shifts in absolute and relative abundance of algae, invertebrates, and fish. Closure to tidal flow reduces water circulation through the ponds and can result in high pH and die-back of macroalgae in low salinity ponds. Seasonal closures to tidal flow also prevents movement of fishes from the Bay into the ponds, and movement among the different ponds.

Efforts to improve the low to moderate salinity salt ponds (20-85 ppt) as wildlife habitats, without interfering with salt production, should focus on controlling dramatic seasonal changes in productivity and species composition found under current operations. These changes appeared to

76

be associated with poor water quality and low primary productivity, which in turn were by-products of salt management practices. This study has shown that macroalgae is a critical resource for fish and invertebrates in the low salinity ponds. Therefore, it is important that conditions which favor the growth of macroalgae are encouraged. While environmental conditions in some ponds were generally suitable for macroalgal growth, especially when salinity was below sea water concentrations and pH was below 9.0, conditions often became unfavorable for macroalgae. Widespread die-backs of macroalgae were associated with high pH and high salinity, and appeared to be the product of seasonal changes in water circulation. Although the closure of the intake pond to tidal flow during the winter and spring maintains salinities at levels necessary for salt harvest, it deprives the pond of low salinity, low pH water, and the circulation which may be necessary to reduce the probability of large scale die-backs of pond macroalgae. Management of low salinity ponds for wildlife may require opening the ponds to tidal flow in spring before salinity and pH concentrations in the ponds approach levels potentially detrimental to algal productivity. Means of providing for movement of fish from the ponds to the Bay should be investigated. Many non-resident fish species in

the ponds are transients in the South Bay and must move down
the estuary to complete their life cycle (i.e., northern
anchovy, shiner surfperch, and striped bass), but are unable
to migrate from the ponds under present flow conditions.

In this study, seasonal changes in salinity within the
high salinity ponds (Ponds All to A15) often produced rapid
and dramatic shifts in fish, invertebrate, and algal species
composition and productivity. These changes in salinity may
be inevitable under present management conditions, but are
unnecessary if the ponds are managed exclusively for
wildlife. Salinities in these ponds should be maintained
above 40-45 ppt to provide conditions suitable for brine
shrimp. If habitat for fish is desired the ponds should be
kept below 75 ppt.

If salt production is abandoned, many salt ponds could
be reclaimed as tidal wetlands, but some might be retained
and managed to provide moderate salinity (40-150 ppt)
habitat for brine shrimp and the fish and birds that have
come to depend on them.

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